MCR-72-169
Contract NAS9-12359

N 73-23853

Volume I

Final Report

December 1972

Summary of Long-Life Assurance Guidelines

Long-Life Assurance Study for Manned Spacecraft Long-Life Hardware

MARTIN MARIETTA

MCR-72-169
Contract NAS9-12359

Volume I	Final Report	December 1972

SUMMARY OF LONG-LIFE ASSURANCE GUIDELINES

LONG-LIFE ASSURANCE STUDY FOR MANNED SPACECRAFT LONG-LIFE HARDWARE

Approved

R. W. Burrows

R. W. Burrows,
Program Manager

MARTIN MARIETTA CORPORATION
P. O. Box 179
Denver, Colorado 80201

FOREWORD

This document is Volume I of a five-volume final report prepared by Martin Marietta Corporation, Denver Division for the National Aeronautics and Space Administration, Manned Spacecraft Center (NASA-MSC) under Contract NAS9-12359, *Long-Life Assurance Study for Manned Spacecraft Long-Life Hardware*. This study was performed with J. B. Fox, Manned Spacecraft Center, as Technical Monitor and R. W. Burrows, Martin Marietta, as Program Manager. Acknowledgment is made to the individual contributors identified in each volume and to R. A. Homan and J. C. DuBuisson, Task Leaders for the electrical/electronic and mechanical areas, respectively.

The five volumes submitted in compliance with Data Requirements List T-732, Line Item 4, are as follows:

Volume I - Summary of Long-Life Assurance Guidelines;

Volume II - Long-Life Assurance Studies of EEE Parts and Packaging;

Volume III - Long-Life Assurance Studies of Components;

Volume IV - Special Long-Life Assurance Studies;

Volume V - Long-Life Assurance Test and Study Recommendations.

Many of the issues discussed are controversial and while the recommended guidelines are believed to represent the concensus opinion, it should be recognized that some guidelines may require tailoring to specific program constraints and objectives.

CONTENTS

I. INTRODUCTION

INTRODUCTION

The objective of the Long-Life Assurance Study was the development of design, process, test, and application guidelines for achieving reliable spacecraft hardware with a life of 10 years or more.

The study approach consisted of an intensive review of technical data performed concurrently with a comprehensive survey of the aerospace industry. The data reviewed included design and operating characteristics, failure histories and solutions, and NASA-Alerts. The reference and bibliography sections of the individual studies cite a total of 628 documents. The industry survey consisted of discussions with about 190 companies and government agencies. For maximum cost-effectiveness, trips were minimized, but over 550 telephone conferences were held.

Significant technology transfer occurred during this study program. For example, the data exchanged during the study of temperature cycling acceptance testing was observed to have an immediate beneficial influence on the policies and procedures of TRW, Lockheed, Aerospace, JPL, and Martin Marietta Aerospace. This indicates that the studies have the potential for significant technology transfer within the aerospace industry. In addition, non-aerospace industry should also benefit whenever the objective is long-life and high reliability.

Twenty-six studies were performed. Table 1 lists these studies and the applicable volumes.

This volume (Volume I) is a summary of the guidelines developed in the studies of Volumes II, III and IV. The guideline format employs an introductory statement regarding hardware long-life failure problems and presents the following topics:

1) Design Guidelines

2) Process Control Guidelines

3) Test Guidelines

4) Application Guidelines

5) Special Considerations

Table 1 List of Long-Life Assurance Studies and Volumes

<u>EEE Parts and Packaging (Volume II)</u>

1) Monolithic Integrated Circuits
2) Hybrid Integrated Circuits
3) Transistors
4) Diodes
5) Capacitors
6) Relays
7) Switches and Circuit Breakers
8) Electronic Packaging

<u>Components (Volume III)</u>

9) Electric Motors and Bearings
10) Accelerometers
11) Gyroscopes and Bearings
12) Compressors and Pumps
13) Magnetic Tape Recorders
14) Plumbing Components and Tubing
15) Check Valves
16) Pressure Regulators and Solenoid Valves
17) Thermal Control Valves
18) Pressure Vessels and Positive Expulsion Devices
19) Ni-Cd Batteries
20) Transducers

<u>Special Studies (Volume IV)</u>

21) Temperature Cycling as Employed in the Production Acceptance Testing of Electronic Assemblies ("Black Boxes")
22) Accelerated Testing Techniques
23) Electronic Part Screening Techniques
24) Industry Survey of Electronic Part Derating Practice
25) Vibration Life Extension of Printed Circuit Board Assemblies
26) Tolerance Funnelling and Test Requirements

For ease of cross-referencing, the guidelines in this volume are in the same sequence as the studies in Volumes II, III and IV. Section II of this volume covers the guidelines developed from Volume II (Electronic Parts and Packaging), Section III covers the guidelines from Volume III (Components), and Section IV covers guidelines from Volume IV (Special Studies). During the final review of Volume I (the last volume published), a few minor clarifications were incorporated. Therefore, the guidelines of Volume I should govern, in the few cases where the guidelines are not identical.

These guidelines, about 650 in number, illustrate that long life hardware is achieved through meticulous attention to many details and no simple set of rules can suffice. These guidelines constitute a valuable foundation of knowledge for long-life hardware program engineers, and in addition, may be employed by program managers as a checklist to establish the degree of conformance and the areas of risk on any given program.

II. LONG-LIFE ASSURANCE GUIDELINES FOR EEE PARTS AND PACKAGING FROM VOLUME II

A. GUIDELINES FOR MONOLITHIC INTEGRATED CIRCUITS

The life expectancy of properly constructed and applied integrated circuits is greatly in excess of 10 years. Failures are caused first by defects introducted during manufacture and second by errors in test, handling, and application. Wearout is only a minor problem that is alleviated by derating. The guidelines that follow are addressed to the major problems with integrated circuits. These problems, for the most prevalent to the least prevalent, are:

1. Particulate contamination

2. Metallization opens from improper metallization, scratches, micro-cracks, and migration

3. Internal wire bond failures

4. Package integrity problems

5. Problems from failure to use a monometallic system

6. Ionic contamination due to surface contamination or to the internal atmosphere

The use of Mil-Std 883 and Mil-M-38510 will detect the gross failures in high volume production but these specifications are considered inadequate for non-maintainable long-life spacecraft. These specifications should be augmented to require an improved pre-cap visual inspection, scanning electron microscope inspection at the water level, surface protection by glassivation, non-destructive bond pull testing, eutectic die bonding, and a serial sequence (rather than a parallel sequence) of environmental and life testing to detect the additive degradation encountered in actual use. Some of the currently specified testing can be eliminated when the above are specified. In addition, Method 2012 of Mil-Std 883 contains inadequate X-ray inspection and rejection criteria and needs to be revised in order to detect faults currently being experienced.

1. Design Guidelines

1) Use phosphosilicate glass over the thermal oxide with a maximum thickness of 0.24 micron to getter surface sodium contamination.

2) Use silicon nitride or other glassification over the chip to protect the SiO_2/Si interface from external sources of channel-including contamination, immobilize residual contamination, and protect the chip surface from handling damage and particulate shorts. Since glass will not adhere satisfactorily to gold, the moly-gold system will require an additional layer of molybdenum atop the gold.

3) Use eutectic alloy bonding of chip to header which will withstand 300°C storage temperature without degradation because epoxy or other polymer bonds do not provide the bond strength, the thermal conductivity, or the temperature capability of eutectic bonds. (Does not apply to beam lead or flip chip devices.)

4) Use a monometallic system for chip metalization, interconnect wires, and bonding pads of external leads to eliminate formation of intermetallic compounds that result in poor bonds. There are no established advantages in the use of either aluminum or gold with respect to the effects of radiation of space or nuclear power sources such as RTGs.

5) When using aluminum metalization, the thickness must be at least 10,000 Å to avoid oxide step defects, window microcracks, and dangerously thin metalizations.

6) Maximum design-use aluminum current density must be 5×10^4 amp/cm^2 to minimize electromigration effects.

7) Use high-temperature glass in package lead seals because low-temperature glass has high lead oxide content that can be reduced and short external leads.

8) Use hermetically sealed packages only with a maximum leak rate of 1×10^{-8} Atm cc/sec to eliminate contamination of the integrated circuit from external use ambients. Plastic, epoxy, and silicone encapsulation methods are not presently developed to the point where moisture traveling up the lead has been satisfactorily controlled, or to the point where uniformity of materials and processing has been established within the industry.

9) Prohibit use of cadmium-plated packages and control use of organic material because nonsubliming materials are preferred in space applications. Acceptable package materials are Kovar, gold-plated Kovar, or nickel.

10) The TO-type can and the flat pack are preferred packages for long life usage.

2. Process Control Guidelines

1) Use metalization deposition processes and annealing procedures that result in large uniform grain structures with a minimum grain size of 8 microns to minimize electromigration effects. Wafer should be heated to 300°C or greater during deposition.

2) Use a planetary deposition system for metalization to eliminate shadowing at oxide steps.

3) The following processes must be reviewed and assurance obtained that they are adequate, stabilized, and under proper control by the manufacturers to minimize contamination and metalization imperfections, and to provide high yield, stability, and precise characteristics.

    a) Thorough wafer cleaning at each process step.

    b) Precise mask layout, dimensional control, alignment, and exposure.

    c) Uniform resistivity of basic wafer.

    d) Purity of photoresist, proper application, spin, and bake.

    e) Thorough resist development and post-development inspection.

    f) Controlled depth, rate, angle, and undercut of oxide etch processes and thorough post-etch inspection.

    g) Thorough resist removal

    h) Precise diffusion or deposition and drive-in, reoxidation purity.

    i) Precise oxide growth, removal, and epitaxial growth.

3. Test Guidelines

1) 100% electrical testing and burn-in for a minimum of 240 hours is mandatory for screening out defective devices. For programs requiring the highest reliability, consideration must be given to burn-in for longer than 240 hours, or at higher temperatures, because the internal elements of integrated circuits cannot be stressed to their rated capability.

2) 100% Pre-cap visual inspection to standards superior to that required by Mil-Std-883 is required to detect time-dependent failure mechanisms resulting from scratches, pin-holes, residues and improperly controlled processing.

3) 100% bond pull testing is currently quite controversial, but is recommended herein because it is being successfully performed by Autonetics, Fairchild, and others, and without evidence of the possible degradation postulated by the companies that have not investigated and adopted this techniques. Bond pull tests are needed since the acceleration and shock tests do not detect bad bonds because of the very small mass of the wire involved.

4) Submit a wafer sample from each metalization run to a detailed scanning electron microscope inspection to assure uniform and continuous metalization over window cuts and oxide steps, to avoid undercutting and water fall effects from oxide etch, to detect oversintering, and to verify mask alignment. Inspection at the wafer level is the most economical point in the process sequence for performance. Screening tests are not 100% effect in detecting these faults and further costly processing is avoided.

5) Submit a wafer sample from each metalization run to a profilometer test to verify metalization thickness and avoid electromigration problems.

6) Perform the qualification tests of Group C in MIL-M-38510 in sequence on the same group of parts as opposed to performing the tests in parallel. This will impose the additive effects of environments that are more realistic to real life use. Also, the screening effectiveness can be evaluated.

3) Use parts that are available form several sources in active production. During a long-term program, the probability of a single supplier discontinuing production is increased.

4) Identify a production lot of all parts resulting from a single metalization deposition run because the metalization deposition process is responsible for some failures.

4. Application Guidelines

1) Circuit voltage transients should be limited and static charge precautions should be followed in handling because built-in protective circuits are not generally provided and circuit damage must be avoided.

2) Case temperature should be limited to 85°C to minimize temperature-dependent failure mechanisms.

3) Current-limiting should be provided when interfacing with the similar circuits so that power dissipation limits will not be exceeded.

4) Reduce fanout to 80% of the rated maximum to increase reliability by derating.

5) Derate linear circuits as follows so that end of life drift characteristics will be considered in product design.

   a) Initial offset voltage, $\pm\frac{1}{2}$ mv

   b) Initial bias current, X2

   c) Offset current, X2

   d) Open-loop gain, ±20%

   e) Slew rate, ±20%

   f) Common mode rejection, ±20%

   g) Power supply rejection, ±20%.

5. Special Considerations

1) Use established processes and material/process combinations whose failure mechanisms are well known. New or unique processes, such as amorphous semiconductors are characterized by a lack of understanding of the basic principles by which they operate. Failure mechanisms, life capability, and reliability are unknown.

2) Use parts with established reliability history as first choice, considering the possibility that parts with the longest history may be superseded by improved techniques of design or processing. Parts without sufficient data must be thoroughly evaluated before approval.

B. GUIDELINES FOR HYBRID INTEGRATED CIRCUITS

The life expectancy of properly designed and fabricated hybrid integrated circuits is in excess of 10 years. However, monolithic integrated circuits are preferred to hybrid circuits in long life applications. The processes involved in the momentum of hybrid devices creates an increased probability of problems which impact reliability, yield, and cost. Hybrid integrated circuits should be used only when an objective trade-off analyses has concluded that their advantage of higher packaging density outweighs the risks. This conclusion applies to true hybrids containing resistors and other parts. Where the hybrid contains only I.C. die, the reliability risk is similar to that of an equivalent array of monolithic integrated circuits. The guidelines identified herein will enable use of hybrids with minimum likelihood of failure and maximum service life.

1. Design Guidelines

1) Use Bismuth-Ruthenium Oxide, Thallium, or Iridium as thick film resistor materials for greatest stability. Palladium and silver should be prohibited because of instability in reducing atmosphere (palladium) and migration (silver).

2) Palladium-gold or platinum-gold is preferred for thick film conductors. Silver should be prohibited to avoid migration at conductor-resistor interfaces.

3) Substrate thickness should be no less than 20 mils to avoid breakage problems.

4) Gold-silicon eutectic bonding of semiconductor chips is mandatory for highest reliability. Gold filled solder paste should only be used when eutectic temperatures cannot be used. Glass frit may fracture with thermal and mechanical stress. Epoxies, silicones, and other plastic or resinous materials have long term degradational effects.

5) Flip-chip, LID's, and beam lead devices should not be used due to limited availability of devices. The LID's cannot be thoroughly inspected and few hybrid fabricators can process flip chips reliably. Although the beam lead is extremely promising, the attachment processes are insufficiently established and practiced throughout industry at this time.

6) Use the metal lid and base type package. The ceramic package can result in photoelectric currents within active circuits. In the larger package, extreme care is required to prevent generation of solder balls or internal weld splatter in scaling.

7) Prohibit electroplating of thick film materials to avoid corrosion problems.

8) Submit each circuit to a worst case analysis. To assure long-life operation, the analysis should be based on end of life tolerances.

9) Use gold or gold on nichrome for thin film conductors because of documented life and stability capability.

10) Nichrome resistors should be coated with silicon dioxide to act as a moisture barrier.

11) Packages should be backfilled with inert, dry gas to minimize corrosion.

12) Although no sufficiently proven processes exist to date, an internal coating material appears highly desirable. The material should (1) act as a moisture barrier, and (2) immobilize particulate contamination.

2. Process Control Guidelines

The following processes must be reviewed and assurance obtained that they are adequate, stabilized, and under proper control by the manufacturers to minimize defects and to provide high yield, stability, and precise characteristics.

1) Substrate layouts avoiding thermal concentrations.

2) Precise mask preparation to provide resistors within acceptable trimming limits.

3) Thin film deposition control for proper film adhesion, within-tolerance resistors, and good drift and TCR characteristics.

4) Resistor trimming operation to maintain required tolerances.

5) Substrate and chip bonding processes for mechanical strength, good thermal conductivity, and minimal parametric change with age.

6) Wire bonding for mechanical strength and geometries avoiding shorts.

7) Thick film drying and baking processes to avoid outgassing and provide film stability.

8) Sealing process to provide hermeticity and prevent corrosion and drift from environments.

3. Test Guidelines

1) Individual chip families utilized such as resistors, capacitors, or semiconductors should be qualified to ensure basic capabilities of the devices used.

2) The supplier and the hybrid processes used should also be qualified for assurance of basic capability. The use of a standard "qualification model" hybrid for this use would minimize the requirements for qualification of individual circuit designs.

3) The conventional screen tests of MIL-STD-883, Method 5004 are adequate for hybrid integrated circuits.

4) Screening of individual chip devices including burn-in, thermal shock, and high temperature storage should be performed to the maximum extent possible. This will assure chip devices with a minimum probability of defects and increase yield. Semiconductor chips are not suitable for burn-in at the present time except for LID and beam leaded devices.

4. Application Guidelines

1) Circuit voltage transients should be limited and static charge precautions should be followed in handling because built-in protective circuits are not generally provided and circuit damage must be avoided.

2) Case temperature should be limited to 80°C to minimize temperature dependent failure mechanisms.

3) Current-limiting should be provided when interfacing with the similar circuits so that power dissipation limits will not be exceeded.

4) Reduce fanout to 80% of the rated maximum to increase reliability by derating.

5) Derate linear circuits as follows so that end of life drift characteristics will be considered in product design.

   a) Initial offset voltage, $\pm\frac{1}{2}$ mv

   b) Initial bias current, X2

   c) Offset current, X2

   d) Open-loop gain, ±20%

   e) Slew rate, ±20%

   f) Common mode rejection, ±20%

   g) Power supply rejection, ±20%.

5. Special Considerations

1) Select suppliers with a successful history of fabricating similar parts. Hybrids requiring techniques and materials unique to his normal practice may be reliability risks because of the lack of experience.

2) The supplier's use of the required processes should be continuous to avoid reliability risks from start-up operations.

3) Packaging and handling must be controlled to minimize exposure to electrostatic charges.

C. GUIDELINES FOR TRANSISTORS

The storage and service life of a properly assembled, tested and applied transistor is virtually unlimited. Predominant in-service failures are due to surface contamination causing parametric degradation and ultimate shorting, particulate contamination resulting in shorts, and interconnect wire failure causing opens. Use of the selection, screening, application and handling guidelines included herein will enable transistors with a minimum probability of defects and practically indefinite service life.

1. Design Guidelines

1) Use silicon planar die constructions. Mesa, grown junction, alloy, or germanium types have serious life limiting problems. Mesa constructions, however, are necessary in large power, high voltage devices.

2) Use die with thermally grown oxides since silicones and varnishes introduce undesirable surface contaminants.

3) Phosphosilicate glass passivation over thermal oxides and metallization is recommended to better surface contaminants and protect metallization.

4) Aluminum metallizations should be at least 10,000 Å thick to avoid thinning over oxide steps and be of sufficient cross-sectional area to limit current density to 5×10^4 amps per square centimeter to reduce effect of electromigration (primarily for devices with expanded contacts).

5) Do not use polymer or glass frit die attachments since they do not afford the thermal conductivity or mechanical strength of eutectic die attachment. (Soft solders for some power devices is unavoidable, but not preferred.)

6) For large die, temperature compensation phases, such as molybdenum tabs or ceramic wafers, should be employed to prevent die cracking under thermal stress.

7) Where the die is dielectrically isolated from the case, both die and isolator must be eutectically mounted to afford minimum thermal impedance and maximum strength.

8) Monometallic interconnect systems are preferred to eliminate intermetallic related bond failures. Gold-gold is the most preferred, but least available. Al-Al is acceptable only when the wire is ultrasonically bonded and 7 to 10 wire diameters slack is left between post and die. Gold-aluminum is acceptable only from suppliers who have demonstrated consistent success with this type of interconnection.

9) Hermetically sealed packages (10^{-8} ATM/cc/sec) must be used for encapsulation of the die since epoxies, plastics, and other encapsulants do not afford adequate moisture protection.

10) Dry inert back-fill gas within the package must be present to prevent interaction of the gas ambient with the die materials.

11) Inert non-reactive materials must be used for package and lead materials and platings to preclude package degradation due to corrosion or contamination and must provide sufficient mechanical strength to withstand handling, shipping and installation environments.

2. Process Control Guidelines

1) Process controls used by manufacturers are usually implied by the severity of screening and qualification tests required. Controls implemented will usually be sufficient to afford reasonably high screening yields: (i.e., 20-50% of initial lot will survive screening tests).

2) Diligence of the part manufacturer in controlling cleanliness, assembly, inspection and handling of the parts can best be monitored by the user through 100% pre-cap visual, source inspection, lot acceptance testing, and fingerprinting (construction analysis).

3. Test Guidelines

1) A 100% non-destructive interconnect wire pull is recommended to eliminate defective wire bonds. Sound bonds will not be degraded.

2) A rigorous pre-cap visual inspection of the die and header assembly is essential to eliminate common assembly defects. Perform die inspection (preferably at the wafer or die level) to eliminate defective die.

3) Screening tests on 100% of the parts, which include burn-in, HTRB, thermal cycling, mechanical shock, hermeticity, and parametric tests are essential to eliminate defective parts.

4) Qualification tests are performed once on a group of candidate parts. These tests are arranged in a manner aimed at specific failure mechanisms. The qualification also includes characterization and fingerprinting of the device to establish a baseline for validity of the qualification for future procurements. The fingerprint is performed on each successive lot to determine conditions which could invalidate qualification. Part type remains qualified as long as screening results, acceptance test results, and part performance are acceptable.

4. Application Guidelines

1) The part must be properly specified electrically and mechanically. The part must be capable of meeting the needs of the circuit without exceeding its abilities. Otherwise serious overstress of sound parts could result.

2) Maximum voltage and current ratings should be derated to 75% of rating to provide safe operating margins in the application.

3) Junction temperature should be maintained below 110°C for all silicon devices to reduce effects of thermal stresses and related metallurgical changes within the part.

4) Time/temperature dependence of part parameters should be determined and appropriate circuit derating applied to accommodate end of life drift of performance parameters; e.g., gain, switching speed, etc.

5) Mechanical installation of the part must provide adequate thermal transfer and preclude severe mechanical stresses.

6) Low leakage devices should be protected from high voltage, low energy transients, such as electrostatic discharges to preclude junction degradation.

5. Special Considerations

1) Part types selected should be fabricated using material/process combinations that are understood and whose failure mechanisms are known. Screening can only be effective when it is aimed at known failure mechanisms.

2) Part types with established reliability afford high confidence with minimum qualification and evaluation effort; however, obsolescence and design utility are key factors in part selection. Types with limited history must be thoroughly evaluated for potential reliability problems.

3) Parts should be selected which are available from several sources to avoid procurement problems if one supplier discontinues production or has difficulty with production.

4) Sources selected should have a stable labor, facilities, and management situation. The part selected should be in reasonably continuous production and be fixed in design and characteristics. Larger volume manufacturers, although somewhat more independent, afford more lot to lot homogeneity than their smaller competitors.

5) Lot traceability back to pre-cap visual inspection is desirable to identify potential lot problems if in-service failures are encountered.

D. GUIDELINES FOR DIODES

The storage and service life of a diode that is well constructed and properly applied is greater than ten years. Life limitations are due to failures caused by defects rather than life limiting wearout mechanisms.

Part screening techniques normally restrict part failures to the part manufacturer's facility. Better wafer scribing techniques, in-line checks for bulk silicon defects, oscilloscope display tests, parameter drift detection, and acoustical noise tests will minimize the probability of receiving defective parts.

1. Design Guidelines

1) Use phosphosilicate glass for glassivation of die surfaces. The phosphosilicate is desired because of its characteristic to act as a gettering agent for sodium.

2) Use silicon nitride (Si_3N_4) as it protects junctions from degradation from the mobile ions such as sodium. Si_3N_4 alone is insufficient as process control is difficult and demonstration of control is as much a requirement as the presence of the Si_3N_4.

3) Utilize laser, chemical or ultrasonic scribing techniques to prevent cracks that occur during diamond scribing.

4) Use scanning oscillator-techniques (SOT) to aid in detecting bulk failures, such as dislocations, that occur during the processing stages.

2. Process Control Guidelines

a. Demonstration - The part manufacturer should demonstrate process control effectiveness. This should be in the form of records that show increasing or stable yields for the processes in question or in the form of test data (from periodic testing) that shows decreasing or stable reject rates. Data of this nature will demonstrate that the processes are being controlled effectively. Other results may indicate inadequate process control.

b. Check Points - The part manufacturer should have in-line check points that verify that the process is in control. An example of this is a lead bond pull test of a sample of units taken from the line in a periodic manner. Consistent or increasing bond pull values would be indicative of lead bond process control. Varying or decreasing values would be indicative of inadequate process control or personnel variations.

3. Test Guidelines

Testing must be based on the results of the evaluation of the part. Tests may vary from part to part depending on construction and function.

1) The qualification testing described in Volume II should be performed on each procurement lot. These tests will verify part fabrication process control that could vary from lot to lot. The stress levels will be governed by the system requirements.

2) The screen tests described in Volume II should be performed on all parts to be used in the fabrication of production hardware. These tests will detect gross mechanical defects and defects that result in electrical parameter variations and early life failures.

3) Use oscilloscope display tests since they are more effective than automatic test equipment in detecting parts with anomalies. The oscilloscope display will aid in detecting unstable parts by exhibiting the breakdown characteristics.

4) Electrical parameter measurements must be made before, during and after burn-in or life testing to determine which parts are stable. Parameters may drift initially and then stabilize at a new level. Measurements of this kind would preclude rejection of stable parts.

5) Tests designed to detect particles such as weld splatter or solder balls should be implemented. The monitored vibration test and the Particle Impact Noise Detection (PIND) test are both effective.

6) High temperature bias must be performed on planar type diodes. The exposure to voltage or current and temperature will detect inversion or accumulation defects.

7) Burn-in for all parts is recommended.

4. Application Guidelines

1) Current and voltage derating must be required. This derating will maintain lower junction temperatures and protect against spurious surges. Current and voltage must be derated 50%.

2) Stud torque and seating plane flatness must be controlled to prevent excessive stresses in the die/header interface and to promote better heat transfer.

3) Limit operating junction temperature to 110°C to achieve longer life.

4) Provide stress relief of leads and interconnecting wires to prevent damage to the hermetic seal of the part.

5. Special Considerations

1) Current ratings in terms of lead temperature versus lead length must be established. This kind of information is useful to a designer for calculating heat sinking requirements and will standardize current ratings.

2) A manufacturer selection must be performed. Selection criteria consists of a history survey, process maturity verification, and part evaluation. This will aid in selecting the best part.

E. GUIDELINES FOR TANTALUM CAPACITORS

The guidelines are for the following types of tantalum capacitors:

1) Solid electrolyte, sintered slug;

2) Wet electrolyte, foil;

    a. Plain foil,

    b. Etched foil,

3) Wet electrolyte, sintered slug.

Tantalum electrolytic capacitors provide large values of capacitance per unit volume, but they are less reliable than other types. For example, six tantalum capacitor failures occurred in the Mariner Venus 67 spacecraft program. The total capacitor usage was 4622 parts of which 1301 were tantalums. No failures occurred in the other capacitor types.

The life expectancy of properly constructed, tested, and applied tantalum foil and solid electrolyte capacitors is in excess of 100,000 hours. The quality of these parts is due largely to good control of critical materials and complex processes. However, many failures have occurred from errors such as lead welding, slug soldering, insulation sleeve defects, etc. The wet slug tantalum capacitor is not recommended for long-life applications at this time. The preferred choice for long-life applications is the solid electrolyte capacitor. Wet slug capacitors should be permitted only if their use has been specifically justified. When used, the electronic packaging design should permit their replacement without damage to other parts.

The guidelines presented herein will enable use of tantalum capacitors with minimum probability of defects and maximum service life. Guidelines for wet electrolyte slug capacitors have been included even through the solid electrolyte slug capacitor is the preferred choice for long-life applications.

1. Design Guidelines

1) Use only hermetically sealed capacitors to provide maximum stability and reliability, and prevent outgassing during low pressure operations.

2) For foil and wet slug capacitors, the leads should be welded to anodized tantalum risers external to the hermetic seal so as to provide a completely insulated structure within the seal.

3) The tantalum riser wires should not extend more than 1/4 inch beyond the seal to minimize the possibility of bending and therefore damaging the riser and its oxide, particularly at the seal area.

4) The cathode lead of wet slug capacitors in silver cans should be of a material which is weldable to silver without causing crystallization or punch-through. For this purpose, silver or oxygen free copper is superior to other materials such as nickel.

5) Gelled electrolyte is preferred over liquid sulfuric acid electrolyte in wet slug capacitors because of lesser mobility.

6) The proper high temperature solder must be used in fabrication to prevent reflow during assembly operations.

7) The attachment of slugs into solid electrolyte capacitor cases must utilize silver bearing solder to prevent silver paint dissolving into the solder.

8) Plain foil capacitors are preferred over the etched foil, since the etched foil is somewhat more prone to manufacturing process errors.

2. Process Control Guidelines

In general it is not necessary nor desirable for the user to control the processes of the tantalum capacitor manufacturer. Variations in processes, equally successful and equally proprietary, exist. Each manufacturer, however, must have his particular processes under strict control. The lack of control will usually be reflected in wide product variations and poor yield. As a guideline, however, the user should not wait for these effects to manifest themselves, but should obtain maximum supplier cooperation and monitor him as closely and continuously as possible.

3. Test Guidelines

1) Tantalum capcitors should be qualified to the requirements of MIL-C-39003 or MIL-C-39006 level P, as a minimum. Additional program-peculiar requirements should be added as required.

2) Radiographic inspection on 100% of the devices should be made in accordance with more comprehensive inspection criteria such as in MSFC-STD-355 to detect anomalies more effectively.

3) Burn-in should be increased to a minimum of 240 hours at rated voltage at 85°C with tight delta limit criteria. Stability is an indication of reliability and present durations are not sufficiently long to detect all parts with instabilities. Read and record measurements of capacitance, dissipation factor, and leakage should be made before and after burn-in on 100% of the devices.

4) Seal test should be performed on 100% of the devices to verify every seal. In addition, if acid electrolyte is used, a litmus paper or thymol blue test should be added to the usual leak test.

5) Accelerated tests are applicable to solid tantalum capacitors. Caution is required in applying these techniques to foil or wet slug capacitors as electrolyte breakdown may occur at relatively low voltages creating a new failure mechanism.

4. Application Guidelines

1) For highest reliability, polar capacitors should be applied so that voltage reversal never occurs, including the conditions of combined ac and dc voltage.

2) When capacitors are used in series, balancing resistors should be used to assure proper division of voltage.

3) When capacitors are used in banks, they should be assembled in easily removable modules to facilitate replacement and test.

4) Solid electrolyte capacitors should be applied with a limiting series resistor of 3 ohms per volt minimum so that scintillation effects do not precipitate catastrophic breakdown.

5) When solid electrolyte capacitors are used in banks, the series limiting resistor should be installed with each capacitor to prevent discharge of the entire bank into a scintillation fault.

6) The ripple current in all capacitors should be limited to values which do not bring the temperature above the derated rating. When capacitors are used in banks it is cautioned that the capacitor with lowest ESR will carry the largest ripple current.

7) The largest possible case size should be used for a given capacitor voltage rating as this provides thicker oxide dielectric, lower ESR, lower dissipation factor, better heat dissipation, and greater capacitance stability.

8) To minimize silver particle generation, the ripple current for wet slug capacitors should be derated as follows:

   T_1 Case Size - 35 ma RMS

   T_2 Case Size - 120 ma RMS

   T_3 Case Size - 300 ma RMS

9) For long life high reliability usage, the peak voltage including surges and transients should be limited to 50% of the manufacturer's derated ratings for all tantalum capacitors.

10) For foil and solid electrolyte capacitors, the allowable ripple current should be derated to 70% of the manufacturer's derated rating for high reliability.

11) The temperature of solid electrolyte capacitors should be limited to 50°C including internal temperature rise. For long life, the foil and wet slug types should be held to 70°C.

5. Special Considerations

1) When purchasing tantalum capacitors, the lowest failure level available should be used.

2) Flight hardware should use the freshest product available to avoid degradation that may have occurred during shelf life and to take advantage of improved processes and techniques.

3) Whenever wet slug capacitors are used, they should be operated a minimum of 240 hours in the actual use condition. Dissection should then be made and the device observed for silver deposits on the anode and cathode. Evidence indicates that ripple current can plate and deplate silver.

4) Select parts with high volume continuous production and acceptable past history with no likelihood of product line obsolescence to obtain products with maturity.

5) For highest assurance, reject all parts with absolute or delta parameter outlier values. Analyze parameters delta shift data and use only the most stable parts in flight hardware. Perform litmus or thymol blue test on parts containing acid just prior to installation in assembly.

6) Avoid non-standard sizes, ratings, and lead materials to avoid risks associated with manufacturer's lack of experience with such parts.

F. GUIDELINES FOR ELECTROMECHANICAL RELAYS

Relay cycle life varies from 20,000 to more than 1,000,000 cycles depending on the electrical loads on the contacts and the extent the relay is derated. The storage life of hermetically sealed relays, with proper materials and processes employed to eliminate internal outgassing, is in excess of 10 years.

The chief problem in electromechanical relays is contamination. Even if cleaning processes could eliminate all particulates, the problem of internal generation of particles, due to wear, is still present.

An electromechanical relay should not be used when a solid-state switch can satisfy the application, or when the application can be tailored to enable the use of a solid-state switch. When it is necessary to employ electromechanical relays, redundancy should be employed whenever high reliability is required.

The analysis conducted to define the redundancy configuration should not only consider the circuit application, but also the characteristics and failure mechanisms of the specific candidate relay. Failure mechanisms should be explored very thoroughly as the different types of mechanical arrangements combined with manufacturing variability can produce unexpected modes such as partial, intermittent, closing of the relay. The parallel redundant configuration is the most commonly used approach since it protects against the open failure mode resulting from particle contamination. Quad redundancy may be necessary if the potential metallic contamination is large, compared with the contact gap, as has been experienced with some relays. One form of quad redundancy consists of two coils (two relays) with two contacts within each relay.

When the use of relays is unavoidable, the guidelines identified herein will provide relays with a minimum likelihood of failure.

1. Design Guidelines

Design criteria are both application independent and application dependent. The criteria are presented under these two groupings.

a. *Design Guidelines Application Independent*

1) *Hermetic Seal* - Relays should be hermetically sealed for minimum leakage. Electron beam welding should be used. This type seal has the least leakage and introduces practically zero contamination.

2) *Arcing* - Minimize arcing in design by increasing contact gap and opening/closing speed. This design requirement takes precedence over miniaturization.

3) *Contact Action* - Contacts should be designed for a partial wiping action. Partial wiping (0.003") will clean the contacts of small particles, polymers and oxides.

4) *Motor Force* - The motor should be designed with a 20% force margin at minimum operating conditions. Force margin above 20% does not increase reliability.

5) *Getter* - Do not use a getter. If cleaning processes and material selection require a getter, the relay is not a high-rel relay. In addition, getters are a source of particulate contamination.

6) *Pin Seal* - Use compression glass for pin seal. To minimize susceptibility to cracking, undercut the front and back side of header. This will puddle the glass and prevent miniscule creep.

7) *Built-In Devices* - Do not use built-in devices for ac rectification (coil) or induced voltage suppression. These additional components decrease reliability through particle contamination and outgassing.

8) *Armature* - Use balanced clapper armature design. Although other designs appear to have higher reliability possibilities (suspended, rotary, diaphragm), each exhibits a weakness which results in less reliability (shock/vibration, particulate susceptibility, hydrocarbon outgassing).

b. *Design Guidelines Application Dependent*

1) *Contact Material*

a) For dry circuit to intermediate loads, use gold plating on contacts. The softness and inertness of gold reduces susceptibility to film contamination, which is the primary problem in this load range.

b) For intermediate to high loads, use palladium for contact material. The hardness, high melting point and relatively inert properties reduce the susceptibility to material transfer, erosion and carbon generation which is the primary problem at higher loads.

(Note: Load application (resistive, motor, lamp) and the number of cycles which will be required must be analyzed carefully before the choice is made for highest reliability. The cut-off point is approximately two amperes.)

2) *Arcing* - Arc suppression circuit design will affect gap, closing/opening speed, contact material and physical size of relay. This must be considered in parallel with relay design parameters.

3) *Dual-Chamber Relays* - The dual-chamber relay is recommended because it isolates relay contacts from polymers. As polymers primarily affect light circuits, and therefore small relays, their use is limited to this application range; i.e., less than 5 amperes. The cost of dual-chamber relays versus parallel realys may be prohibitive.

4) *Bifurcated Contacts* - Bifurcated contacts are recommended at low and intermediate current ranges since the contact pressure tradeoff is more reliable. Also, certain circuit applications are sensitive to contact bounce. The dual contact can be adjusted for separate resonances, and virtually eliminate energy fluctuation.

5) *Spark Arrester* - The spark arrester is useful in high load, many cycle applications. However, it is a particle and gaseous contaminant generator; and the reliability tradeoff must be made for contamination failure versus contact to case shorting failure. It is recommended for a large number of cycles and not recommended for a low number of of cycles. Approximately 100,000 cycles is the cut-off point (life).

6) *Backfill Gas* - The tradeoff involved with backfill gas is: inert gas versus a gas with some oxygen for lubrication. Unfortunately, oxygen enhances polymer formation in addition to being an oxidizer, Small-ultra-clean-single-cavity-relays should use oxygen. Small dual-chamber relays should use oxygen in the contact chamber. These relays are more susceptible to sticking from self-adhesion due to the small motor forces and the noble metals used on contacts. There is some evidence that oxygen in larger relays is effective in reducing wear and particle contamination, but it is not conclusive.

2. <u>Process Control Guidelines</u>

1) *Coil* - Coil wire lubricant is a major cause of hydrocarbon contamination. Wind the coil, using dry wire. This can be done by immersing the spool in a bath of trichlorethylene and wiping the strand during winding.

2) *Winding* - Coil wire should be pretensioned during winding operations at just below the elastic limit. Scramble wound is preferred, as space factor is just under layer wound, and it is easy.

3) *Component Cleaning* - All subassembly components (armature, frame, can, contacts, header, pins, bobbin, springs and pins) should be cleaned prior to assembly. The recommended cleaning process is ultrasonic trichlorethylene, GN_2 drying, ultrasonic alcohol, GN_2 drying, ultrasonic distilled water followed by GN_2 drying.

4) *Handling* - All handling/moving of components and subassemblies should be done with the components sealed in a plastic bag.

5) *Degassing* - All relays should be subjected to a high temperature, high vacuum degassing process. The vacuum should be less than 5 mm Hg, and the temperature at 200°C for 4 hours minimum. At least one GN_2 purge cycle is recommended. The hydrocarbon outgassing which condenses on the chamber walls should be cleaned after each batch processing.

6) *Sealing* - The evacuation hole should be sealed with a plug, electron beam welded into place <u>BEFORE REMOVING FROM THE BACK-FILL CHAMBER</u>.

7) *Plating* - Plating is a major source of metallic contaminants. Avoid plating, if possible. The plating material, electrolyte, temperature, time, etc., should be very precisely controlled. In addition, samples should be analyzed from EVERY plating lot to assure uniformity, adhesion and porosity of plating.

8) *Raw Materials* - All incoming raw materials shall be subjected to quantitative and qualitative analysis to assure conformity. Do not hesitate to reject incoming materials.

3. Test Guidelines

1) *Qualification Testing* - Qualification testing should subject the relay to 25% environmental overstress condition, while monitoring relay parameters for out-of-limit conditions and uniformity. Qualification testing limits are established by user application.

2) *Screening Tests* - Standards for screening tests of all relays have been established. Since many documents describe these in detail, they are listed below without additional description.

   a) *Pre-Adjust Run-In* - 5000 cycles with no contact load and prior to contact, contact spring, armature gap, and armature spring adjustment.

   b) *Pre-Can Visual* - 100% inspection for particulates prior to canning at 10X magnification.

   c) *Parameter Tests* - These tests should include contact resistance, coil current, coil resistance, pick-up and drop-out voltage, operate and release times, dielectric strength, insulation resistance, gross and fine leak tests, and miss (run-in) tests.

3) *Additional Recommended Tests*

   a) *Shock and Vibration* - 100% shock and vibration tests.

   b) *Lot Sampling*

      - 5% of each lot should be subjected to qualification level (destructive) testing

      - 5% of each lot should be subjected to long shelf-life testing

c) *Particle Detection Test(s)* - Two basic tests exist to detect particulates. Both require the relay to be mechanically agitated. In one, the relay is cycled, and the particulate is captured by the armature or contacts which produces a parametric anomaly. In the other, the energy released by the particulate striking the relay or can is sensed. A variation of either method is to apply a high potential to the case and monitor for a case to relay short.

4. Application Guidelines

1) Many relay failures are caused by misapplication and can be prevented by a detailed application analyses conducted prior to the selection of the relay. This analysis should consider the type of load, the type of power, the load level, the switching requirement and the environment. Refer to Volume II for examples of circuit application.

2) Relays should be located and mounted to minimize the probability of contact chatter or transfer due to shock and vibration. The shock from pyrotechnic sources is a significant problem to relays, which is completely avoidable by the use of solid state switches.

3) Current should be derated as follows:

Type of Load	Percent of Manufacturers Rating
Resistive	75%
Inductive	40%
Motor	20%
Filament	10%
Capacitor	75%

4) Use solid state switches in preference to relays. When relays must be used, employ redundant configurations when high reliability is required.

5) Design the circuits to be switched so that minimum stresses are imposed on the relay contacts.

6) Use arc suppression techniques. Mount arc suppression diodes externally to the relay package.

7) When estimating light cycle requirements, avoid a false life assessment. Count the total cycles to be accrued in manufacturing, acceptance testing and prelaunch checkouts, in addition to the mission usage cycles.

5. Special Considerations

1) A problem encountered with particle detection tests such as the Raytheon test and the Lockhead PIND test is that build-up of static electricity internally in the relay can during vibration causes the contaminant particles to stick to surfaces and reduces the effectiveness of the test. A test program was conducted on this contract to eliminate the static charge build-up by exposing the relay to ionozing gamma radiation using a cobalt 60 source. The test results were negative in that the radiation was not sufficient to loosen the particles. Higher levels of radiation would probably be effective but would be precluded by the resultant hazard to the personnel. An alpha radiation source was also tried and this also produced negative results.

G. GUIDELINES FOR SWITCHES AND CIRCUIT BREAKERS

A major problem with switches is contamination, both particles and contaminant films on contacts. Circuit breakers are less prone to failure from contamination, but are more prone to mechanical failure due to the complexity of some actuation mechanisms. The storage life of switches and circuit breakers exceeds 10 years when the devices are hermetically sealed and internal non-metallic materials are eliminated, or if very stable materials are used. The state-of-the-art cycle life is about 100,000 actuations for switches and 10,000 actuations for circuit breakers. Switches and circuit breakers with less cycle life capability are acceptable when the mission requirement is significantly less than the cycle life capability.

Current developments in solid-state circuit breakers should be continuously reviewed and solid-state circuit breakers used when permitted by availability and application, since they are not subject to wear out or the failure modes inherent in complex mechanical devices.

1. Design Guidelines

1) Use hermetically sealed, metal enclosed switches. Accomplish the seal by electron-beam welding. Soldering or non-metallic sealers introduce both particulate and gaseous contaminates.

2) Use either a metal bellows or metal diaphragm for the seal around the activation mechanism. Do not use an elastomer seal. This metal seal should also be accomplished by electron-beam welding.

3) Circuit breakers are, typically, not hermetically sealed, but sealed devices should be used if and when available.

4) The contacts should be alloys of nickel, silver or palladium for loads greater than 500 milliamperes. For loads less than 500 milliamperes, the contacts should be gold plated to minimize oxide films and maintain low contact resistance.

5) The minimum thickness for gold plating is 0.000100 inch. Thinner platings may burn through. Thicker platings are neither necessary nor cost effective.

6) The contact gap should be sufficient to extinguish the maximum design power arc. This consideration is most applicable to very small switches, such as reed switches.

7) Snap-action switching of contacts should be designed in the mechanism to minimize arcing time which increases contact life.

8) Contacts should have a partial wiping action (0.003" to 0.005") to disrupt oxide films. Greater wiping lengths will introduce excessive wear.

9) External electrical terminals should be sealed with glass with a matched thermal expansion coefficient for strength, dielectric and gas seal qualities. Other methods such as alumina, ceramic sleeves, and brazing are under development but should not be used until the process is developed and proven.

10) Solid-state circuit breakers, currently under development, are preferable to mechanical circuit breakers since they are not subject to wear-out or the failure modes inherent in complex mechanical devices.

11) Solder hook external contacts are required to provide stress relief to the glass seal. Plug-in units are not recommended because the glass seal may be stressed.

12) Getter devices should not be used. They may break or move and interfere with switch operation. Switches must be clean enough without a getter or they are not reliable parts.

13) Avoid plating of internal parts. Plating is a major source of metal particle contamination.

14) Minimize the use of non-metallic materials because they are prone to outgas, are a source of particulate contamination, have a normally lower mechanical strength, are more temperature sensitive, and do not have the long term stability of metals.

2. <u>Process Control Guidelines</u>

1) All switch assembly should take place in a Class 100 clean room environment to preclude particulate contamination; an extremely serious problem.

2) The transfer of switch components between assembly stations should be accomplished in sealed plastic bags to reduce contamination.

3) Vacuum bake-out of switches should be conducted at 200°C, 1 mm pressure for a minimum of four hours to prevent subsequent contaminating films of non-metallic materials. Some components may require as much as 16 hours, two cycles. One purge cycle with dry GN_2 is recommended as a minimum.

4) The out-gassing hole in the switch enclosure should be sealed in the backfill chamber, or an adjacent chamber common to the back-fill chamber to prevent contamination.

5) The back-fill and bake-out chamber should be cleaned after each operation to remove hydrocarbon (oil) condensate from chamber walls.

6) During assembly, each mechanism piece should be checked against the installation print for proper installation. A go/no-go test should be made for every clearance specified, with no hindrance of motion.

7) Plating of piece parts should be avoided. Where unavoidable, the plating process (temperature, raw metal purity, bath cleanliness, voltage stability, etc.) should be continually monitored and controlled. In addition, destructive parts analyses should be conducted on 5% of the piece parts to verify plating adherence, absence of cracks, and the achievement of a fine-grained structure.

8) Cleaning baths should be constantly filtered and recirculated with approximately a 20% replacement after each cleaning process.

9) Incoming material inspection should be on a sample basis as a minimum and should verify materials, dimensions and tolerances as well as workmanship. Materials should be stored in contamination protected containers or bags.

3. Test Guidelines

1) Qualification and acceptance (screening) testing should be accomplished using MIL-S-8805 for switches and MIL-C-39019 for circuit breakers as a minimum. Additional program peculiar requirements should be added as required.

2) For acceptance testing of production hardware, the above specifications are inadequate in certain areas and, therefore, must be supplemented with the following inspections and tests.

3) Radiographic inspection on 100% of the devices should be accomplished in accordance with more comprehensive inspection criteria such as MSFC-STD-355C to detect contamination, bent parts, and misaligned parts.

4) For switches, an operational run-in (2000 cylcles of operation at -65°C, 2000 cycles at +125°C, and 500 cycles at +25°C) should be conducted as a 100% screening test. The voltage drop across the contacts should be monitored during cycling and the electrical characteristics measured after the test. For circuit breakers, the run-in should be performed using 200, 200, and 50 cycles at the applicable temperatures, and with verification of calibration consistency. The values of 2000, and 200, are upper limit values which should be reviewed for reduction to avoid wear-out of some shorter-life devices.

5) Seal tests should be performed on 100% of the devices to verify the seal integrity.

6) A sinewave vibration test of 30g's 5-2000 Hz, should be conducted as part of 100% screening with contact resistances monitored during the test to insure the absence of contact chatter and transfer. During vibration, both switches and circuit breakers should be monitored for a short to case condition, as well as other parameters.

7) A particle contamination test should be performed as a 100% screening test. The (PIND) test per LMSC specification 1420833 is recommended. The Raytheon developed particle detection test has some technical advantages, such as better detection of smaller non-metallic particles. However, this test is more time consuming and costly and, therefore, most part specialists consider the PIND test as more cost-effective.

8) Accelerated testing is basically accomplished by the run-in testing described above. However, one variant which should be considered for selective application is the exposure of the non-operating device to high temperature followed by operation under a very light load to establish that outgassing of inorganic material has not produced a contamination film on the contacts. This accelerated test approach is aimed at a final verification of the adequacy of the bake-out processes.

4. Application Guidelines

1) Current should be derated as follows:

Type of Load	Percent of Manufacturers Rating
Resistive	75%
Inductive	40%
Motor	20%
Filament	10%
Capacitor	75%

2) When estimating life cycle requirements, avoid a false life assessment. Count the total cycles to be accrued in acceptance testing and prelaunch checkouts, in addition to the mission usage cycles.

3) Switch applications in digital circuits must be carefully reviewed to assure that contact bounce or chatter will not be interpreted as a circuit interruption which will produce logic errors.

4) Switches and circuit breakers are subject to contact chatter in high shock and vibration environments, and these environments may dictate the use of solid-state devices. The mounting of switches and circuit breakers should be designed to minimize vibration and shock amplification or to provide the necessary isolation.

5) Where a circuit breaker hang-up or failure to trip can jeopardize the mission, redundant circuit breakers should be used. On the Skylab Program, this is accomplished by having circuit breakers in the various branches of the power distribution tree.

6) Contacts may be paralleled to reduce the effects of contact bounce and vibration, and for redundancy. This purpose has been achieved using bifurcated contacts. NOTE: Do not parallel switch contacts to increase current breaking and making capability. One set of contacts will close first and carry excessive load.

H. GUIDELINE FOR ELECTRONIC PACKAGING

1. Guidelines for Multilayer Printed Circuit Boards

Achievement of long-life multilayer printed circuit boards mainly depends on achieving plated-through holes which are capable of withstanding temperature changes without cracking and electrical failure. Heavy deposits of ductile copper are necessary, and verification by temperature cycling coupons from production boards is mandatory.

a. *Design Guidelines*

1) The thickness of the through-hole should be not less than 0.0015 inch for good resistance to thermal induced cracking.

2) Heavy layer copper (2 ounce) is preferable to 1/2 and 1 ounce circuits, and the thickness of the layer copper and PTH copper should be approximately matched for good resistance to thermal induced cracking.

3) Thinner boards, in which the volumetric proportion of glass epoxy to copper is minimized, are preferable.

4) The standard land, plated-through connection is superior to both functional land and landless designs, from the standpoint of thermal induced cracking.

5) For severe thermal applications, resin-glass systems of low thermal expansion should be developed and used to minimize thermal induced cracking.

b. *Process Control Guidelines*

1) The two processes critical to the life of multilayer printed circuit boards are the hole drilling process and the electroplating process, both of which require very close control to insure clean holes and ductile copper.

2) Brighteners should not be used in the electroplating bath since they may cause brittle copper.

3) The electroplating bath should be very closely controlled to avoid both brittle copper and hard copper.

4) Rockwell B hardness of 50 or less is recommended to assure the ductility necessary for long-life.

c. Test Guidelines

1) A test coupon from each production board containing 80 to 100 plated-through holes, connected in series, should be temperature cycled between -65° and 110°C, and increased electrical resistance should be cause for rejection of the production boards.

2) For programs with a nominally mild temperature environment 50 temperature cycles are recommended. For more severe applications, 200 temperature cycles are recommended.

3) Acceptance tests should also include temperature shock tests simulating the wave, or the hand soldering operations, since thermal induced warping of the boards tends to cause cracks between the inner copper planes and the plated-through hold.

d. Application Guidelines - Multilayer printed circuit boards should not be used in a very severe temperature cycling environment. An example is exposed hardware (not temperature controlled) on a spacecraft in a 150 nautical mile orbit where a temperature cycle is experienced every 1½ hours. However, from the wider viewpoint of overall electronic equipment reliability, electronic equipment should be protected from a severely fluctuating temperature environment by the use of a passive or active environmental control system.

2. Guidelines for Printed Circuit Boards Assemblies

In a printed circuit board assembly, the principal failure mode (exclusing part failures) is cracked solder joints from temperature fluctuations which cause fatigue failures in solder joints not provided with adequate stress relief in the packaging design. (Failures of electronic parts are treated in the other sections of this volume.) The solution to the problem is to design an adequate stress relief. Other factors, such as solder application technique, amount of solder, type of solder alloy, etc., influence solder joint cracking, but are secondary to the factor of stress relief.

a. *Design Guidelines*

1) The parts mounting techniques should be controlled by specification. The specification "Standard Parts Mounting Design Requirements" MSFC-STD-136, is recommended.

2) Plated-through holes provide a much stronger solder joint than bare holes. Bare holes should not be used.

3) The pad size, hole diameter, and all other geometric factors influencing the shear strength of a given solder joint should be kept to the conservative side of MSFC-STD-136 to insure the strongest practicable solder joints.

b. *Process Control Guidelines*

1) NHB 5300.4 (formerly NASA 200.4) is oriented towards the process of producing high quality solder joints. This specification, however, does not provide detailed guidelines on the stress relief of solder joints and, therefore, it should be augmented by the use of MSFC-STD-136.

2) The maximum amount of solder allowed by NHB 5300.4 (formerly NASA 200.4) should be used, since temperature cycling tests have shown that the amount of solder significantly influences solder joint cracking.

3) The gold embrittlement problem should be avoided by removal of the gold-on-gold plated leads prior to the final soldering operation.

c. *Test Guidelines*

1) Verification of the packaging design should be accomplished on *early* prototypes, or on test samples representative of the design, by subjecting the hardware to temperature cycling between -55°C and 100°C, and inspecting for cracked solder joints.

2) The nominal value of 200 cycles required by MSFC-STD-136 is recommended. The actual mission environment should be reviewed to determine if this value should be adjusted.

d. Application Guidelines

Printed circuit board assemblies are not suitable for use in very high vibration and shock environments. For vibration levels of 0 to 5g rms, no particular effort to reduce vibration fatigue effects are usually necessary. From 5 to 20g rms, vibration resistance can usually be achieved through proper use of clamping, dampening, and conformal coating. Above 20g rms, the use of encapsulants to prevent fatigue failures from excessive board flexure will usually be required. The above estimates are gross; and each printed circuit board application requires a careful review for compatibility with the dynamic environment, and to establish mounting and dampening provisions.

e. Special Considerations

The requirement to withstand 200 temperature cycles may seem excessive, but it should be emphasized that earth-based equipment not stored in a temperature controlled environment could acquire 1826 cycles, with about a 15°C daily excursion, in a period of five years, and that some spacecraft equipment may experience a temperature cycle every 1-1/2 hours. The correlation of accelerated temperature testing with field service conditions has not been clearly definitized. However, IBM, on one program, determined from actual failure data that 46 temperature cycles from -20°C to 85°C was equivalent to two years of field service life.

3. Guidelines for Conformal Coating

Conformal coating, necessary for environmental protection and mechanical support on long-life hardware, is a major cause of both part and interconnection failure when not properly selected and applied. The problem is that heavy coatings, heavy filleting, or bridging under flat bottom parts produce or aggravate stress on parts and solder joints in a fluctuating temperature environment, and cause cracked solder joints and damaged parts.

a. Design Guidelines

1) A flexible polyurethane coating less than 4 mils in thickness is recommended.

2) Fragile parts such as glass diodes should be sleeved to prevent damage from thermal expansion stresses.

3) Coatings of the above thickness do not provide ultra high insulation resistance because 100% coverage cannot be achieved. When ultra-high insulation resistance (10^{10} ohms, and above) is required, a deposited coating such as Parylene C is recommended.

4) When both ultra-high insulation resistance and mechanical support is required, a deposited coating such as Parylene C followed by a sprayed 1- to 2-mil flexible polyurethane coating is recommended.

b. Process Control Guidelines

1) The application of conformal coating should be closely controlled by the packaging specification to prevent heavy coatings, heavy filleting, and bridging under flat-bottom parts. Application by spraying and removal of excess filleting by centrifuging (spinning) is recommended.

2) Bridging of conformal coating under flat-bottom parts usually has catastrophic consequences and must be completely avoided.

c. Test Guidelines

1) Verification of the packaging design, with the conformal coating applied, should be accomplished by the temperature cycling program described for printed circuit board assemblies.

2) Assure that the specific polyurethane selected has been tested under high humidity and temperature conditions to assure chemical reversion will not occur.

d. Application Guidelines

1) Conformal coating should be used only when specifically required for humidity protection and/or mechanical support.

4. Guidelines for Encapsulated Modules

Encapsulation (potting), employed with cordwood packaging, and sometimes with printed circuit board construction, is used for increased mechanical support. All potting materials, as a result of temperature changes, impose stresses on parts, connections, and many materials. Stresses in the thousands of pounds per square inch are produced. To prevent failures of parts and connections, the potting material must be carefully selected and then tested using temperature cycling to verify that damage to parts and connections will not occur. Encapsulated modules generally do not have the temperature cycle capability of well-designed printed circuit board assemblies.

a. *Design Guidelines*

1) Solid, rigid materials, such as solid polyurethane or epoxy, should not be used as they impose excessive stress on the encapsulated parts.

2) Microballoon filled epoxy and low density polyurethane foam are usually satisfactory materials.

3) Very low density materials, such as polyurethane foam with a density of 2 lbs/cubic foot, may be required for increased temperature cycling capability.

4) Low density materials are good heat insulators and the module design must allow the conduction and dissipation of self-generated heat.

5) Potting stresses are reduced by a low ratio of potting volume to hardware volume.

6) In encapsulated modules, welded joints are preferred to solder joints since they are not subject to the problem of fatigue cracking.

7) Resilient pre-coats should be employed to achieve lower stress on parts and connections. A thin pre-coat (0.001 inch) hydraulically distributes the stress on a part, while a thick coat (0.008 inch) will reduce the stress.

b. *Process Guidelines*

1) The curing temperature should be as low as practicable, since a zero stress condition is present at the curing temperature, and stress progressively increases as the module cools.

2) Proper allowance must be made for the fact that the manufacturer's recommended curing process will probably not result in a 100% complete cure and subsequent temperature cycling will cause further hardening and aggravate the stress problem.

c. Test Guidelines

To verify that the encapsulating material and process will not damage parts, electrical connections, or cause performance shifts of sensitive parts, it is mandatory that the design be subjected to temperature cycling as described in the section of this report on printed circuit board assemblies. A prime difficulty in such testing is the difficulty of removing the potting to inspect the electrical connections visually. This difficulty is largely alleviated if the recommended, very low density, materials are used since these can usually be removed by mechanical, if not chemical, means.

III. LONG-LIFE ASSURANCE GUIDELINES FOR COMPONENTS FROM VOLUME III.

A. GUIDELINES FOR ELECTRIC MOTORS AND BEARINGS

Ungeared induction motors and permanent magnet (PM) stepper motors are currently operating continuously up to five years in hermetically sealed environments at 1500 rpm. In laboratory conditions, eight years have been accomplished. Other high speed ac motors (brushless) derated to 3000 rpm have achieved up to 3½ year continuous operation with and without gearheads, hermetically sealed or with molecular shaft seals. In all cases, fluid lubricants were used.

Very slow speed brush type motors at 30 rpm are still operating satisfactorily after 4.6 years, but other brush type motors operating at 150 rpm failed after approximately 7 months from either brush, commutator, or lubrication problems. Commutator diameters were almost identical in both instances; thus, the brush linear velocity on failed units was five times that of units still operating. Wet lubes were used in all motors.

Brushless despin motors at 100 rpm, still operating after 3½ years, are destined for a 7-year life.

Apart from the brush problem of dc motors, bearings and their lubrication constitute the primary life limiting feature of motors in satellite applications. The following guidelines concentrate on means to enhance the current state-of-the-art for assurance of optimum life by "designing in" the necessary reliability and life.

1. Design Guidelines

1) Employ minimum gearing between motor and load. Low gear ratios required less gears and bearings and allow larger gears that have more durable gear proportions.

2) Use wet lubricants in preference to solid lubrication (ambient temperatures permitting) because:

    a) Boundary lubrication with wet lub (or grease) is preferable to that obtained with solid lubrication.

    b) Wet lub is a better heat transfer medium, allowing bearings to dissipate conducted or generated heat more readily.

c) Ability of wet lubricants to operate in EHD or partial EHD regime. Life is limited only by lube film endurance; the wear is insignificant.

3) Use a channelling type grease when using grease for rolling contact bearings. This allows the balls to form a channel which the consistance of the grease is designed to sustain. Friction is thereby minimized. Oil will bleed into the ball track from residual grease.

4) For long brush life on dc torquers, utilize cartridge type brushes instead of the usual cantilevered spring type. Longer brush lengths can be used to accommodate the higher brush wear rates in vacuum.

5) Avoid the use of silicone oil in brush type torquer applications. If oil migrates to the commutator, arcing may cause decomposition and result in a film of silicone on the commutator.

6) When using silicone lubricants, pay special attention to the minimizing of oil migration. Barrier films may be used. A preferred alternative is teflon components sandwiched between bearings and housing. Employ teflon coating of molecular shaft seal surface.

7) When using molecular seals and reservoirs, locate reservoirs immediately adjacent to each bearing such that oil migration is facilitated. Bearing lubrication does not rely entirely on vapor consensation.

8) Also, locate a reservoir adjacent to the motor winding to quickly generate an oil vapor following inoperative periods at low temperature.

9) When using molecular seals and reservoirs, prewet all interior surfaces of the motor with a film of oil to avoid unnecessary loss of reservoir content.

10) When using molecular seals and reservoirs, incorporate an air filter into the body of the motor to bypass the majority of air flow from the molecular seal. Filter must provide high laminar flow and low molecular flow compared with the molecular seal. The air filter avoids particulate contamination of bearings and molecular seal.

11) When using molecular seals and reservoirs, in conjunction with a brush type motor, special care must be exercised to maintain an optimum film thickness on the commutator. An excess of oil may be as detrimental as an inadequacy. The optimum film thickness will help optimize brush wear, minimize arcing and avoid lubrication degradation.

12) When using grease lubed ball bearings, select cartridge type bearings (this does not apply to angular contact bearings). These are longer than standard and permit a larger charge of grease.

13) When using shielded bearings, insure that shields are leak-tight where they interface with outer race to prevent creepage loss of lube from bearing.

14) For EHD or partial EHD operating conditions, use precision bearings ABEC 7 or ABEC 9 grade with following overriding tolerance and finish requirements. These are prerequisites for proper EHD or partial EHD operation. When using bearings to the below tolerances, housings and shafts must be manufactured to similar accuracies of peripheral roundness in order to maintain bearing accuracy after installation.

- Race groove, OD and peripheral roundness and eccentricity:	0.000010 in. max TIR
- Cross-Race departure from constant radius (in ball contact region):	0.000010 in. max
- Surface finish - balls:	1 microinch rms
- Surface finish - raceways:	2 microinch rms
- Visible damage, asperities, blemishes (at 40X) on balls or in ball path of raceway:	None
- Ball roundness:	0.000003 inches TIR
- Ball accuracy within any bearing or batch:	0.000005 inches

15) Use 52100 consumable electrode vacuum melted alloy steel bearings except when a corrosion hazard exists, otherwise utilize 440C melted in the same manner. The 52100 exhibits fewer inclusions even when consumable electrode vacuum melted. It also has minimum dimensional change with time.

16) Use ABEC 7 quality bearings for maximum assurance of quality, quality control, precision and cleanliness. When geater clearances than normally associated with the ABEC 7 grade are essential to accommodate for dry film lube thickness, the same quality precision and quality control provisions should be maintained. The same applies to instances where ABEC 9 tolerances may be necessary in order to meet preload or stiffness requirements.

17) Use porous, vacuum oil impregnated ball separators, either laminated phenolic, nylasint or porous polyimid. Emphasis should be placed on using the latter material which, although of recent origin and not cataloged, appears to offer considerable advantage. Polyimid has higher porosity than laminated phenolic, and is more readily (and accurately) machined than nylasint.

18) To accommodate extremes of temperature, anchor the rotor longitudinally with one bearing. Accommodate differential thermal expansion and contraction by allowing axial float on the other bearings. This will avoid excessive thrust loads on bearings due to thermal expansion and/or contraction.

19) To prevent brinnelling of bearings and housing, avoid the arrangement where both bearings float, except under the mildest vibration and temperature environments.

20) Utilize housing materials (beryllium or titanium) with a temperature coefficient of expansion compatible to that of the rotor, when operating temperatures vary widely. This will:

    a) Minimize change of bearing accuracy, dimensions, friction and loading with temperature change;

    b) Permit minimum clearance to be used on the floating bearing, thereby avoiding false brinnelling between housing and outer race;

c) Permit smaller air gap (better motor efficiency);

d) Minimize thermal strains between stator and housing.

21) Alternately to 24) use "compatibility" bushings in the housing for the same reasons; except the last.

22) Use symmetrical bearing housing geometry to avoid distortion of bearing bores (and of the installed bearings) due to assymmetrical temperature expansions or contractions.

23) Close control of the housing/bearing and shaft/bearing fits are essential. The degree of interference changes bearing clearances and contact angle; and in the case of duplex preloaded bearings, spring rate is modified. Hence, when these parameters are important, bearing bores and OD's should be custom coded so that they can be matched to housings which provide the required fit.

24) It must not be assumed that the catalog recommended fits for a particular bearing will suffice when minimal lubricant films are involved. This is particularly true where a temperature differential may develop between inner and outer race. Clearance fits may be necessary under room temperature assembly conditions in order to acquire optimum running conditions at operating temperature. Material selection for shaft and housing may have to be determined on the basis of these considerations. Fits must be individually computed in such circumstances.

25) Mechanical worst case analysis should be invoked to give maximum visibility to the combined effects of environment extremes in conjunction with manufacturing tolerances (including eccentricities, nonparallelisms) and the effects of operating temperature. Such analysis shall constitute a permanent part of the design record and be subject to approval by the contractor. Worse-case analysis will:

a) Provide a cost effectivity measure to minimize development and qualification problems;

b) Assure that manufacturing tolerances are determined systematically, not arbitrarily; i.e., their full ramification on motor or bearing configuration being duly evaluated by means of the worst-case analysis;

c) Force consideration of the effects of temperatures, systematically evaluated and not left to intuition;

d) Insure close control on the tolerances and factors which influence bearing misalignment.

2. Process Control Guidelines

1) Demand white room assembly and packaging to Federal Standard 209a, Class 100. Also, require ultrasonic cleaning of parts followed by a wash and particle count. Cleanliness is essential for low friction, low wear and maximum life, especially for high speed applications and EHD operation.

2) Individually inspect each bearing and its components for accuracy and maintain a permanent record of the following parameters:

a) Raceway peripheral roundness and wavyness;

b) Eccentricity of ball path to OD or ID;

c) Cross-race profile at ball path;

d) Surface finish of balls and raceways;

e) Boundary dimensions;

f) Ball retainer dimensions including the bearing land diameter and roundness where it engages raceway;

g) Electronic (noise) analysis of the assembled bearing as a further check on integrity of running surfaces.

h) Breakaway and/or running torque.

3) Inspect all raceways for imperfections using a 40X minimum magnification. There shall be no evidence of inclusions, comets, furrows or pits in the ball path. These will help optimize conditions leading to prolonged lubricated life.

4) Inspect ball retainers not only for accuracy and cleanliness, but also for complete freedom from burrs. Burrs constitute a serious contamination hazard in that they can work free during the life of the bearing.

5) Exercise extreme care when cleaning and vacuum impregnating. Use procedures developed by NASA Goddard as a guide. These ensure through removal of preservative oil applied by the bearing manufacturer, satisfactory wettable surfaces and maximum oil capacity of the porous material.

6) Lubricant or preservative should be applied to bearing using a 30-micron absolute filter on the syringe* (i.e., ASTM 325 mesh screen) for added assurance of lubricant cleanliness.

7) Contamination level of lubricant to be strictly observed and checked by QC prior to use. For greases, the following cleanliness level shall be observed:

   - In any m/litre of grease there shall be no more than 1000 particles between 25 and 75 microns and no particles in excess of 75 microns.†

8) For oil lubricants invoke National Aerospace Standard 1638, Class 0, for added assurance of lubricant cleanliness.

9) Each batch of lubricant shall be individually tested to insure that properties are within specification. This shall include evaporation rate, viscosity, vapor pressure, pour point and viscosity index as a minimum. This will avoid the wide variation of properties for which different batches of the "same lubricant" are notorious.

10) Bearings utilizing dry film lubricants shall be run-in to develop a tenacious ball track. Following this operation, the bearing shields shall be removed and debris resulting from the run-in shall be removed. This run-in may be accomplished prior to assembly into the motor whenever ball loading can be accurately simulated as in the case of angular contact bearings. This should alleviate contamination as a failure mode.

---

*These are tentative suggestions pending further investigation into the topic.

†This cleanliness level is being proposed for Revision B of MIL-G-81322 and represents optimum cleanliness, such greases being made under white-room conditions.

11) Bearing installation in housings shall be conducted in accordance with a written procedure under rigid inspection. This process is critical to proper bearing operation and must be performed with care and precision. The written procedure is to insure that the same (satisfactory) procedure is followed on subsequent production lots.

12) When ultrasonically cleaning assembled bearings, they shall be suspended and not allowed go rest on the bottom of the tank. This avoids false brinnelling hazard.

13) White room assembly conditons (properly supervised and controlled) should be regarded as essential for the more critical motor applications, particularly those involving EHD lubrication. Laminar flow bench assembly and test should be adequate for motors of less criticality; i.e., of low speed or where brushes will quickly generate debris. However, items such as bearings, which are white room processed, must be depackaged on the laminar flow bench.

14) Inspect commutator for freedom from burrs to eliminate brush wear hazard and possible bearing contamination hazard.

3. Test Guidelines

1) There is no point in qualifying a purely nominal configuration when it is the extremes of manufacturing tolerances which present the maximum hazard. A realistic qualification policy is required. Multiple qualification test units shall be employed, (in a cost effective manner) embodying the worst case extremes of manufacturing tolerances such that qualification can be considered to cover any permutation of manufacturing variables.

2) Acceptance testing shall include an extended run-in test where load, environment and heat sinking is simulated.* This shall be followed by a room temperature baseline performance test. Performance, including winding resistance and bearing or bearing housing temperatures, shall be continuously monitored.

---

*Usually of several hours duration, depending on service life and duty cycle. As much as 200 hours have been demanded; the longer periods pertain to geared head motors to detect infant mortality of the slower bearings.

This record shall extend to any prior wear-in or run-in process during manufacturing and shall evidence no perturbation from normality. Bearing noise should be intermittently monitored. The test provides an opportunity for "infant mortality" failure mechanisms to develop and any other abnormality trend to be detected.

3) Testing of bearings has been largely covered under the topic of Process Controls, where noise and breakaway torque tests are specified. Also recommended are stringent microscopic tests of individual components, which could also be regarded as tests.

A test instituted for gyro bearings, measures surface wettability, assessing the surface for contaminations which negate the effectivness of fluid lubricants. It is submitted that the wettability test be conducted either periodically or once per production run. This would assure cleanliness of processes, and check on housekeeping measures and white room atmospheres.

4. Application Guidelines

1) For motors that will be repetitively subjected to Earth environment and space vacuum; (i.e., Shuttle operation) the following policies are recommended:

a) Use hermetically sealed motors and gearheads when the output shaft speed is 200 rpm* or less and wet lub is feasiible. This excludes contaminating and humid conditions when in the Earth environment. It avoids outgassing contaminant from the motor and prevent lubrication loss by evaporation when in space.

b) When a brush type dc motor is employed above -10°F, and the service life is less than 400 hours, utilize a moisture content in the encapsulated gas of 2 grains of H_2O/lb of air in conjunction with high altitude carbon-graphite brushes. Moisture acts as a lubricant for carbon-graphite.

---

*This speed limit is somewhat arbitrary; it is assumed that below this speed torque levels should be high enough to handle the additional load of the hermetic sealing without serious penalty.

c) In lieu of Item b) above, consider the use of a direct acting frameless dc torquer, with or without brushes. Use a molecular shaft seal. The advantages are simplicity, sturdiness and elimination of high speed bearings and gears.

d) For high speed motor applications (no gearhead), use molecular shaft seal and lubricant reservoir system. This type of seal introduces no torque penalty.

e) On slow speed, high torque applications, elastomeric shaft seals may be feasible to enable the motor to be pressurized with an inert gas (i.e., power hinges on booms). Elastomeric seals will exclude contaminating and humid conditions when in the earth environment. They also avoid the complexity of hermetic sealing and prevent lubrication loss by evaporation.

f) Use either metallic or viton bellows for sealing motor actuators with linear output. Pressurize interior to ½ atmospheres with inert gas. This will exclude contaminating and humid conditions when in earth environment. It will prevent lubricant loss by evaporation in space.

2) In high vibration applications, design the rotor assembly such that its resonant frequency is substantially above the maximum input frequency. Using a duplex angular contact bearing at one end of the rotor and a radially preloaded bearing at the other end can facilitate this. Match bearing spring rates as closely as possible. These approaches will minimize amplification of input G levels to ameliorate false brinnelling hazard to bearings.

3) Alternatively to the above 2), the use of vibration isolators should be investigated to ameliorate false brinnelling hazard to bearings.

4) Use low speed, multipole, pancake motors in preference to high speed motors. The shorter, bearing span in the motor provides a higher natural frequency to the rotor shaft. Also, better heat transfer from winding through the casing to the heat sink (bypassing gearing) is provided. They can be mounted more solidly, reducing vibration amplification.

5) Use the largest bearings consistent with design constraints. Larger bearings are: better resistant to brinelling and false brinelling, have lower contact stresses (longer fatigue life), and are stiffer (higher natural frequency).

B. GUIDELINES FOR ACCELEROMETERS

Of the three types of accelerometers considered, only the force feedback pendulous (or proof mass) type accelerometer has the potential for performance over the extended time. With the incorporation of proper design practices, manufacturing and test processes, a ten year life, operating or non-operating, is obtainable. Bias and scale factor must be measured periodically because of instability. Some recalibration will be required. Trends in scale factor changes can be shown from the periodic test data that are accountable by permanent magnet aging. The only significant item that ages is the permanent magnet material which follows a predictable time relationship.

1. Design Guidelines

1) Use pendulous or proof mass accelerometer with force feedback. It has no rubbing or mechanical friction in the design. The technology has been developed to a state where long-life is inherent in the design.

2) Use fluid filled accelerometers; they can withstand the environmental effects of pyro shock and vibration.

3) Select a basic accelerometer capable of greater performance than is required. Performance margin will result in fewer specification requirements because the scale factor degrades with time and the bias instability has long term trends.

4) Employ a magnet with a higher shape factor (L/D) to increase the remanence stability. Also, the higher the coercive force the more stable will be the remanence. Highly crystal oriented ALNICO-5 is significantly more stable than the normal random oriented materials.

5) Use pure properly treated metals to enhance long-life performance by reducing microcreep.

2. Process Control Guidelines

1) Cleanliness of the inert fluid is mandatory to prevent contamination. There have been a number of instances of contamination failure in space vehicles. Furthermore, cleanliness of all instrument materials is generally mandatory.

2) Precondition material to reduce creep and to enhance magnetic stability. These instabilities are greater at the outset of the performance life. Employ artificial magnet remanence reproduction by temperature cycling or small ac fields. The remanence of a magnet will be stabilized.

3. Test Guidelines

1) Periodic tests, depending upon specific requirements for the accelerometer, will be required to determine trends and for recalibration for changes that occur in bias and scale factor.

2) There is no known accelerated testing technique on complete accelerometer assemblies.

3) Screening processes or wear-in tests are sometimes employed for assembled accelerometers (beyond the standard checkout and acceptance testing). Since accelerometers are semi-passive devices, such tests are not universally employed. Wear-in is most applicable to the PIGA accelerometer because this type is subject to wear when it contains ball bearings.

4. Special Considerations

1) Use designs with a proven history and experience because the potential problems of unknown and new designs is a major risk over the extended time period.

2) Either exercise or change the "storage" position periodically to prevent adjustment change of the critical axis bias. Long storage in the same position can affect accuracy.

C. GUIDELINES FOR GYROSCOPES AND BEARINGS

The major problem with gyroscopes is the wheel bearing reliability since its life ranges from 3000 to 10,000 hours. Testing of the gyros for incipient gyro failure during this interval of time is necessary in some applications. Other life limiting factors are the permanent magnet torquers, contamination, and instability in the material causing excessive drift rate.

1. Design Guidelines

1) If the mission requirement is for long-life with interrupted operations, especially in severe mechanical environments, the bearing choice favors a ball bearing wheel gyro because bearing failure takes place over a period of hundreds of hours and the ability to restart is predictable from test data.

2) If the mission requirement for long-life is for uninterrupted operation, the bearing choice favors the gas bearing because there is no wear under run conditions. If the application permits continuous operation, a gas bearing gyro should be used because it permits increased performance and minimal frictional wear in the bearing due to start-stops.

3) If there is a mature existing design that meets the identical new gyro requirements, use it in preference to a new design. A new development is a potential source for major problems.

4) Exacting design, manufacturing, and design for manufacturing is important for a successful product because material creep, chemical compatibility and design to prevent voids and sharp edges has proven necessary by experience.

5) Use the lowest operating temperature for the gyroscope commensurate with the application because chemical action in the lubricant decreases with decreased temperature.

6) Incorporate spin motor rotation detection in the design to permit run-down testing at the systems level.

2. Process Control Guidelines

1) Extreme cleanliness in the manufacturing process is essential because dirt particles as small as 0.001 grams can cause excessive drift in certain applications.

3. <u>Test Guidelines</u>

1) Monitor gyro parameter operating levels and stabilities to establish a record against which observed changes can be evaluated.

4. <u>Application Guidelines</u>

1) Be certain that the gyroscope specifications meet or exceeds the application requirements for all parameters. The most critical parameters pertaining to reliability are vibration, temperature, shock and acceleration.

2) Redundancy options must consider the more gradual failure of the ball bearing gyro as opposed to the almost instantaneous seizure when the gas bearing fails.

5. <u>Special Consideration</u>

1) The production run of wheels in any gyro program should include a quality monitoring plan in which sample wheels are operated to failure according to appropriately specified failure criteria. These wheels should then be inspected for the condition of the materials in the wheel assembly. The results which represent typical conditions of the entire run, provides a basis for extrapolation of wheel failure rates, operating life, and reliability factors. They also provide a basis for failure analysis, product and yield improvement, and comparison with similar records from other programs.

D. GUIDELINES FOR COMPRESSORS AND PUMPS

Continuous operation of compressors, fans, or pumps for two to three years is within the present state-of-the-art. The life-limiting failure modes for these components are listed below in the order of problem magnitude:

1) Bearings and lubrication problems;

2) Seal leakage;

3) External housing leakage;

4) Structural failure of internal moving parts (fan blades, impellers, etc).

1. Design Guidelines

1) The optimum thermal control system design for long-life is a passive system. However, manned space missions require active systems which include such components as compressors, fans and pumps. Their applications are: molecular sieves, ventilation systems, coolant recirculatory systems, life support systems, waste management, and water systems.

2) All agencies surveyed considered bearings to be a major life-limiting problem for compressors, fans and pumps. The operating life of compressors, fans, and pumps can be extended by accomplishing the following:

   a. Fabricating bearing material free from inclusions;

   b. Improving geometry (waviness) of the raceway:

   c. Improving surface finish, and;

   d. Maintaining lubricant thickness.

3) System designs which are adaptable to replacement of components (plug-in or snap-in type) are desirable and should be investigated for long-life applications.

4) Require a vacuum melt or remelt process for metallic bearings. Metallic bearings must be free of inclusions or stringers for long-life applications.

5) Minimize the air gap in magnetic coupling to improve efficiency and promote long-life.

6) Use inert fluids for coolant system applications because of handling ease, they are dielectrics and they are good lubricants for system components.

7) Use wet motors (canned pump and motor) or magnetic couplings to avoid shaft seals which are a source of leakage, contamination and unpredictable drag.

8) Solve housing leakage in fluid systems by:

   a. Impregnation of castings with sealant substance;

   b. Using vacuum melt material to eliminate stringers or inclusions, and;

   c. Weld external pump housing joints.

2. Process Control Guidelines

1) The procurement specification pertaining to compressor, fan, and pump bearings (high speed, long-life, and heavily loaded) when used in failure critical applications, should contain a proviso for 100% dye penetrant inspection on balls prior to installation in bearings.

2) Use castings that are impregnated with a sealant or housing material that have been through a vacuum melt process to reduce inclusions or stringers.

3. Test Guidelines

1) Conduct 100 hour run-in tests prior to flight to eliminate components with latent manufacturing defects.

2) Conduct life endurance tests under operational conditions. For long-life applications, (data are not available for these units), the life parameters must be established.

3) Perform special bearing inspections to control quantity and contamination of lubricant. This action tends to narrow the wide variation of the applied lubricant.

4. Application Guidelines

1) The Gemini, Apollo and Skylab Program designs indicate that journal bearings have been used exclusively for pumps and that ball bearings have been used exclusively for fans and compressors.

2) The present approach does not develop long-life components, but selects components that have been proven on previous programs. Examples from the Skylab program (approximately nine months flight time) include:

   a. Coolant pumps are not replaceable; therefore the pumps are used in standby redundant configurations. Redundant coolant loops are provided.

   b. Redundancy and spare fans and compressors are employed.

5. Special Considerations

1) It is recommended that research into new state-of-the-art advances for long-life assurance include:

   a. The long term electrochemical effects of materials and fluids;

   b. The possible use of ceramic or air bearings instead of carbon-graphite for bearings;

   c. Methods to reduce wear particle generation;

   d. Material compatibility selection characteristics, and;

   e. Continuing effort for bearing development.

2) In spite of the adverse affects, current program decisions (such as Skylab) have been to power down systems during storage periods (approximately 30 to 60 days). Component starting and stopping transients will result in temperature excursions, distortions, stresses and cause part wearout.

3) A cost tradeoff study is needed to evaluate whether a concerted effort needs to be performed to extend the life of compressors, fans, and pumps or whether maintenance and restoration can be performed on these components for extended mission utility.

E. GUIDELINES FOR MAGNETIC TAPE RECORDERS

The major life limiting parts of the magnetic tape recorder are the magnetic tape, magnetic head, bearings, and drive belts. The solution to the drive belt problem appears to be direct drive design. For manned missions, the magnetic tape wear problem will disappear if the tapes are replaced prior to wearout. A continuously operating tape recorder with a two-year life is within the state of the art. A five year continuously operating recorder can be developed with a low-speed record and medium speed playback. Technology exists to obtain 50,000 tape cycles with optimum tape and transport design.

1. Design Guidelines

1) The materials used for the front face of the head should be harder than Rockwell 100B to reduce headwear, drag and debris generation. Use one of the ferrite alloys such as "Alfesil," "Spinalloy," or "Alfenol."

2) Do not use a section of heat cleaning tape on one end of the tape reel to remove debris, glaze and gap smear. Although an apparent short term answer, use of head cleaning tape aggravates wear and subsequent debris formation in long term applications.

3) Employ only instrumentation magnetic tapes and transports with a history of superior performance in spacecraft applications to increase the probability of success.

4) Use NASA/GFSC specification S-715-P-14 which delineates specifications for selecting and using magnetic tape.

5) Limit the maximum stress level in mylar tape to 3000 psi to avoid a region of non-linearity in the region of 8000 to 9000 psi. Keep the tape pack winding tension low to prevent tape deformation.

6) Don't use endless loop transports. They tend to jam or throw loops. Without optimum design a balance between these two failures is difficult to maintain.

7) Avoid drive belts which are life limited primarily because of delamination. Use direct drive motors.

8) Minimize the following, consistent with constraints to reduce head and tape wear:

   a. Tape velocity;

   b. Tape wrap angle;

   c. Head radius.

9) Consider the merits of the high reliability five-year tape recorder system designed by IIT Research Institute for NASA/Goddard as a design baseline. They recommended a reel-to-reel coplanar configuration with independently motor driven reels and capstans.

10) Investigate the feasibility of eliminating multispeed requirements by using a semiconductor or magnetic buffer for input/output of data and parallel recording on multiple tracks.

11) Limit the lubricant in the tape binder to the range of 1% to 2% of the total weight of the binder system. Large amounts of lubricant will weaken the binder while small amounts will not reduce the coefficient of friction adequately.

12) Minimize the number and complexity of moving parts to increase reliability.

13) Minimize interacting mechanical functions to prevent serially adding functions.

14) Keep the rotational velocity of bearings relatively low to help assure long-life. (Too low a rotational velocity will aggravate wear owing to a lack of hydrodynamic lubrication.)

15) Provide bearing lubricant reservoirs to replenish losses.

2. Process Control Guidelines

1) Limit voids or gaps between laminations or other discontinuities on the front face to less than 50 microinches in width. Also, there should be no scratch in the direction of tape motion on the contact surface of the head that is deeper than 12 microinches. There should be no scratches perpendicular to the direction of tape motion. Compliance with the preceeding will reduce the probability of tape damage and decrease the rate of debris accumulation.

2) Cleanliness in assembly is essential to prevent contamination effects. Class 100 clean rooms are suggested.

3) Closely align the gap and apex of the head by observing and maximizing the amplitude of the signal. Misalignment is more critical with the new harder head materials since misalignment cannot be lapped-in from the passage of tape as with soft core heads.

4) Specify and test for the desired tape characteristics rather than attempt to control manufacturing processes since many processes are proprietary.

3. Test Guidelines

1) Thermal cycle head windings and joints six times between -10°C to +66°C to detect open or short failure modes.

2) Subject tape test specimen to the tests outlined in NASA/GSFC Specification S-715-P-14 to assure the tape has certain desirable characteristics. These tests include:

   a. Thermal stability;

   b. Lubricant content;

   c. Surface resistivity;

   d. Chlorine content;

   e. DC noise test (oxide dispersion evaluation);

   f. Flexibility test.

4. Application Guidelines

1) Keep the temperature of the tape below 35°C to prevent binder softening and subsequent iron oxide nodule formation.

2) Store tape at 30% RH, at a temperature less than 32.2°C, and in an argon atmosphere to retard aging degradation.

3) Wear-in the head-tape combination to be used in service to reduce tape abrasiveness and eliminate infant mortality. Specification S-715-P-14 recommends 200 passes.

5. Special Considerations

1) Consider continuing development of a fluid filled type of transport that immerses the tape, heads and bearings in lubricant to alleviate many of the wear and lubricant depletion problems. Emphasis should be placed on increasing the recording density (bits/inch) to that of other recorders.

2) An additional study of alternatives to magnetic tape recorders should be conducted to ascertain optimum data storage/retrieval systems for specific missions. Alternatives should include optical/thermal, magnetic disc, silicon drum, dynamic MOS RAM's and magnetic bubble techniques.

3) Consider, for manned missions, the utility Modular Maintenance concept as a limited-life-component-replacement-methodology to reduce replacement time and installation error probability.

4) Use digital recording if constraints permit. Digital recording permits saturation recording and re-clocking to remove jitter.

5) Investigate the feasibility of air bearings for continuously operating recorders. Because of start-stop wear, air bearings are not suitable for intermittent operation.

6) Determine the areas of airborne aerospace applications of rotary head recorders. The data from the ERTS program should be useful.

F. GUIDELINES FOR PLUMBING COMPONENTS AND TUBING

The service lives of lines and fittings are good for ten years. Although spacecraft systems have not met this goal, aircraft systems have satisfied this requirement.

The life limiting failure modes for lines and fittings (listed in the order of most probable occurrence) are:

1) Leakage of separable or permanent joints;

2) Leakage of plumbing or hose, and;

3) Burst/rupture of separable joints, permanent joints, plumbing, or hose.

1. Design Guidelines

1) Maximize the use of permanent type joints. Improper installation techniques were noted as the major cause for tubing and fitting service failures. Permanent fittings:

   a. Represent a reduced weight when compared to separable fittings;

   b. Reduce system leakage;

   c. Automatic programming equipment produces consistent results;

   d. In case of an unacceptable brazed joint, the number of reheat cycles shall be limited to three, and;

   e. In case of an unacceptable welded joint, the number of reheat cycles shall be limited to one.

2) Suggestions for separable fittings;

   a. Seal problems can be solved by replacing the seal, if separate seals are employed;

   b. Thread failures can be remedied by:

      - Providing for nut replacement capability;
      - Assuring the failure occurs in the replaceable nut. The threaded female flange must be made of harder material, and;
      - Using stub ACME threads, they would reduce thread failures.

3) Design must require alignment fixtures for tubing. Otherwise proper alignment of parts cannot be made with the welding head or the braze fitting, during manufacture when joining tube ends.

4) Locate plumbing fittings and components so that the joints can be made in a horizontal axis for installation ease.

5) To avoid elastomer damage within components or fittings, the temperature gradient of tubing during brazing or welding operations must be a considerations.

6) Weld fittings shall be machined from plate stock only. Utilizing plate rather than bar stock will minimize the possibility of leakage.

7) Weld fluid associated components to next adjoining part rather than braze. This avoids final acid treatment on tube stubs after the individual component has been assembled.

8) Limit the use of hose. The use of flexible tubing reduces the system leakage.

2. Process Control Guidelines

1) Specify tubing ovality to be 3% maximum. Excessive tube ovality creates stresses which reduce the service life of the system tubing.

2) Cleaning process should require that tubes be rinsed with demineralized water and force dried. Recent problems on the Skylab program indicated that solvent vapor degreasing resulted in strains and pitting on stainless steel tubing.

3) Brazing requires cleanliness such as a Code 3 clean area to affect a good joint.

3. Test Guidelines

1) It is recommended that testing techniques be developed which closely simulate actual usage conditions.

2) Failures generated in burst, impulse, or flexure rarely occur in service.

3) The major portion of field failures are related to:

   a. Tubing/fitting installation;

   b. Tubing/fitting fabrication, and;

   c. Long lengths of unsupported tubing that fail during vibration.

4) Advanced flexure testing methods developed for tubing/fitting problems are:

   a. Rotary or planar centilever flexure, and;

   b. Planar vibration free-free beam.

4. Special Considerations

1) Develop qualified in-flight leak repair technology for space applications.

2) The total length of piping used on the DC-10 is 53% more than that used on the DC-8. Important trends are evident:

   a. 70% of the B-nuts have been eliminated;

   b. Brazed or swaged joints are used instead of B-nuts by a factor of 4 to 1;

   c. Use of flexible tubing has increased;

   d. Use of flexible hose has decreased, and;

   e. 97% of "O" ring seals have been eliminated by the use of metal seals.

3) The commercial aircraft panel reported that the five major problems causing 52% of the aircraft delay were:

   a. "B" nuts;

   b. Seal replacements;

   c. Fittings;

   d. Flexible hose, and;

   e. Tubing.

G. GUIDELINES FOR CHECK VALVES

Check valve service lives of 10 years without maintenance are achievable. The check valve cycle life ranges from 250,000 cycles for use in high pressure systems to 500,000 cycles for use in low pressure systems. The current state-of-the-art check valves are satisfactory for programs requiring long service life, such as the Shuttle program. However, cycle life may be a problem for the 500 mission goal of the Shuttle. Preliminary analysis shows qualification life requirements of order $.5 - 1.0 \times 10^6$ cycles.

Internal check valve leakage due to contamination was the main life-limiting failure mode identified from the survey of manufacturers and users. Listed in the order of most probable occurrence, the failure modes are:

1) Internal leakage, caused by valve failing to close or stuck open, seat leakage or chattering of the poppet;

2) Poppet fails to open;

3) External Leakage around the static seals and through the valve body.

1. Design Guidelines

1) Design large flow paths (areas) through poppet check valves and main sealing surfaces to reduce flow velocities and erosion of seats.

2) Configure valve housings (as far as possible) to eliminate areas that can entrap contaminants. Use a "swept by" design where flow will tend to pass contaminants through the valve.

3) Insure that materials are compatible with the working fluid including maximum expected fluid impurities. The evaluation must consider dynamic as well as static applications and must consider temperature, pressure, and phase variations of the fluid.

4) Minimize valve induced contamination:

a. Material selection should consider the effect of wear particle size on useful life. Particle sizes vary as the Young's Modules divided by the square of the compressive yield stress;

b. Use rolled threads in preference to machined threads to minimize burrs and achieve higher strength;

c. Minimize dead-end passages and capillary size passages.

5) Leaks due to contamination are minimized if the seat load is sufficient to plastically yield a trapped contaminant particle on the sealing surface. System contaminants must be identified to determine particle size and material properties.

6) Avoid sliding parts; they not only induce contamination, but entrap contamination.

7) Develop valving elements with quick opening areas to preclude chattering, instability and high seat velocities.

8) Do not use ball check valves as they tend to chatter, particularly on rapid closure of the valve element.

9) Spherical or tapered poppets are recommended. These poppets are self-aligning, but require precise alignment of the valve seat and the poppet assembly.

10) Insure guiding of poppet onto valve seat to allow for maximum alignment and eccentricity tolerance (i.e., use a large length/diameter bearing surface to guide ratio - minimum 2:1).

11) Justify not employing elastomer seats. Low leakage rate requirements (less than 5 scc/hr) can be most easily met by elastomer seats. Since low seat stresses are desirable for long life, high safety factors should be used in conjunction with high seat loads. Control the undesirable creep or cold flow characteristics of Teflon seats by:

a. Containment of Teflon seats on three sides;

b. Heat stabilization techniques;

c. Low stress levels.

12) Avoid Teflon seals for high pressure oxygen system applications to preclude flammability hazards.

13) Seat stress of plastic seats must be held well below material yield stress for long-life storage to prevent excessive deformation. Stress in elastomeric seals is generally not critical.

14) Wear is minimized by making the hard seat in the housing wider than the plastic seal of the poppet or conversely by making the metal sealing surface of the poppet wider than the plastic seat.

15) Smooth surface finishes are superior for long life; therefore, it is recommended a finish of 16 - 32 rms be used.

16) Lipseals supported with a back-up ring to resist undesirable influences of pressure loading are superior to designs without this provision. It is recommended that lipseals guiding piston rods or poppets use backup sealing rings in addition to the main lipseal.

17) Avoid plastically deformed soft metals. This configuration has excellent sealing characteristics, but exhibits low life.

18) Do not use large flat plastic poppet sealing interfaces. They are not compatible with long-life due to high impact wear characteristics and misalignment.

19) Provide positive stops at the end of travel to minimize transient stresses due to poppet travel.

20) Seal retention methods shall prevent seal distortion, creep or dislodgement.

21) The inherently larger leakage rates of hard on hard seat configurations can be minimized by lapping poppet and seat to obtain better seat finishes.

22) Reduce life due to vibration sensitivity is minimized by decreasing available clearances in bearings and guides, avoiding large overhung moments, and restraining lateral motion of poppets.

23) Provide external fittings to permit drain, flush and purge after exposure to propellants.

24) Control stress corrosion by avoiding stress corrosion susceptible materials and/or design parts to operate at low stress levels.

25) Attempt to eliminate dynamic seals. They are subject to wear and cause unpredictable drag.

26) Control external check valve leakage by:

    a. Requiring welded valve body construction;

    b. Require vacuum melt bar stock;

    c. Impregnate valve casting with sealant.

2. Process Control Guidelines

1) Ultrasonically clean valve parts; assemble in specified level-clean areas; and govern by a single contamination control specification during test. This time control specification should also govern the test fluid media used.

2) Use a fabrication barrier (bag) to protect clean parts. Consider using nylon or polyethylene to prevent creation of contamination due to chaffing of the barrier by the parts.

3) Vendor controls shall guarantee that the valve contamination particle size and count will not exceed specified limits. Documentation is required.

3. Test Guidelines

1) Conduct contamination susceptibility tests during development to determine the level of contaminant that the valve can tolerate.

2) To verify valve operation, conduct 50 to 100 run-in cycles.

3) Do not rapid cycle valves designed for fluid applications for functional verification in a dry condition because the lack of fluid damping can increase seat stress and reduce life.

4) Consider techniques to stabilize cold flow. Initial analyses of an accelerated test for Teflon valve seat poppet assemblies indicate that if the assembly is subjected to normal design loads and 150°C temperature for 14 days, then the assembly would not experience any more appreciable cold flow in a ten year period.

5) Conduct life cycle endurance tests under operational conditions. For long-life applications, the valve cycle life parameter must be known.

4. Applications Guidelines

1) A solution to long-life and reliability problems is the application of check valves into redundant configurations. Examples: Several companies have developed either a series parallel check valve (quad valve) with integral filters or a series type check valve with double seats.

2) Install valves into functional groups within systems using permanent connections, such as welded or brazed connections to avoid contamination and to prevent leakage. This type of installation would allow a group of valves to be replaced in event of a malfunction.

3) Check valves cannot normally be repaired by inflight maintenance procedures.

H. GUIDELINES FOR PRESSURE REGULATORS AND SOLENOID VALVES

The current state-of-the-art solenoid valves and pressure regulators can meet the anticipated requirements for long-life applications such as the Shuttle program. Both spring return solenoid valves and pressure reducing regulators can currently obtain calendar service lives of 10 years without maintenance. For gas applications, a solenoid valve cycle life of 500,000 cycles is currently possible; and 1,000,000 cycle life is obtainable with an advanced state-of-the-art valve. A pressure regulator cycle life of 500,000 cycles is currently possible; a cycle life of 1,000,000 is obtainable for environmental control system (ECS) applications.

Internal leakage caused by contamination is the major life-limiting failure mode for the valves studied. The contamination may be from either the fluid medium or from valve wear particles. Listed in the order of most probable occurrence, the solenoid valve failure modes are:

1) Internal Leakage;

2) Failure to open or close, and;

3) External leakage.

Listed in the order of most probable occurrence, the pressure regulator failure modes are:

1) Internal Leakage;

2) Regulator Fails Open or Regulates High;

3) Regulator Fails Closed or Regulates Low, and;

4) External Leakage.

1. Design Guidelines

1) Design large flow paths (areas) through poppet solenoid valves and main sealing surfaces to reduce flow velocities and erosion of seats.

2) Configure housings (as far as possible) to eliminate areas that can entrap contaminants. Use a "swept by" design where flow will tend to pass contaminants through the component.

3) Insure that materials are compatible with the working fluid including maximum expected fluid impurities. The evaluation must consider dynamic as well as static applications. It must also consider temperature, pressure, and phase variations of the fluid.

4) Minimize component induced contamination:

   a. Material selection should consider the effect of wear particle size on useful life. Particle sizes vary as The Young's Modulus divided by the square of the compressive yield stress;

   b. Use rolled threads in preference to machined threads to minimize burrs and achieve higher strength;

   c. Minimize dead-end passages and capillary size passages.

5) Leaks due to contamination are minimized if the seat loads are sufficient to plastically yield a trapped contaminant particle on the sealing surface. System contaminants must be identified to determine particle size and material properties.

6) Avoid sliding parts; they not only induce contamination, but entrap contamination.

7) Develop valving elements with quick opening areas to preclude chattering, instability and high seat velocities.

8) Spherical or tapered poppets are recommended. These poppets are self-aligning, but require precise alignment of the seat and the poppet assembly.

9) Insure guiding of poppet onto seat to allow for maximum alignment and eccentricity tolerance (i.e., use a large length/diameter bearing surface to guide ratio - minimum 2:1).

10) Justify not employing elastomer seats. Low leakage rate requirements of less than 5 scc/hr can be most easily met by elastomer seats.

11) Since low seat stresses are desirable for long life, high safety factors should be used in conjunction with high seat loads.

12) Control the undesirable creep or cold flow characteristics of Teflon seats by:

    a. Containment of Teflon seats on three sides;

    b. Heat stabilization techniques, and;

    c. Low stress levels.

13) Avoid Teflon seals for high pressure oxygen system applications to preclude flammability hazards.

14) Seat stress of plastic seats must be held well below material yield stress for long-life storage to prevent excessive deformation. Stresses in elastomeric seals are generally not critical.

15) Wear is minimized by making the hard seat in the housing wider than the plastic seal of the poppet or conversely by making the metal sealing surface of the poppet wider than the plastic seat.

16) Smooth surface finishes are superior for long life; therefore, it is recommended a finish of 16 - 32 rms be used.

17) Lipseals supported with a back-up ring to resist undesirable influences of pressure loading are superior to designs without this provision. It is recommended that lipseals guiding piston rods or poppets use back-up sealing rings in addition to the main lipseal.

18) Cold-formed plastic lipseals and certain machined plastic lipseals that rely on diametrical stretch to effect a seal such as rotating butterfly valves should not be used for long life applications due to the high frictional wear characteristics.

19) Avoid plastically deformed soft metals. This configuration has excellent sealing characteristics, but exhibits low life.

20) Do not use large flat plastic poppet sealing interfaces. They are not compatible with long-life due to high impact wear characteristics and misalignment.

21) Elastomeric seals may be contained by mechanical or bonding methods. Use bonded seals only where proven in application and use 100% nondestructive test inspections.

22) To minimize transient stresses due to poppet travel, provide positive stops at the end of travel.

23) Seal retention methods shall prevent seal distortion, creep or dislodgement.

24) The inherently larger leakage rates of hard or hard seat configurations can be minimized by lapping poppet and seat to obtain better seat finishes.

25) Reduced life due to vibration sensitivity is minimized by decreasing clearances in bearings and guides, avoiding large overhung moments, and restraining lateral motion of poppets.

26) Provide external fittings to permit drain, flush and purge after exposure to propellants.

27) Control stress corrosion by avoiding stress corrosion susceptible materials or design parts to operate at low stress levels.

28) Justify the use of dynamic seals. They are subject to wear and cause unpredictable drag.

29) Control external leakage by:

   a. Requiring welded valve body construction;

   b. Require vacuum melt bar stock, and;

   c. Impregnate valve casting with sealant.

30) Avoid tapered plug valves and gate valves since they are susceptible to sticking.

31) The solenoid open and close force margins goal is 300%. Failure of the poppet to open (or close) may be caused by binding of the plunger or insufficient solenoid force.

32) Prevent insulation deterioration and subsequent solenoid shorts that can lead to reduction in electromagnetic force by:

    a. Coating solenoid valve lead wires with an abrasive resistance covering;

    b. Take special precautions when joining the lead wire to the solenoid coil wire, and;

    c. Pot coils and lead wires to prevent movement during vibration and operation.

2. Process Control Guidelines

1) Ultrasonically clean valve parts; assemble in specified level-clean areas, and govern by a single contamination control specification during test. This same control specification should also govern the test fluid media used.

2) Use a fabrication barrier (bag) to protect clean parts. Consider using nylon or polyethylene to prevent creation of contamination due to chaffing of the barrier by the parts.

3) Vendor controls shall guarantee that the valve contamination particle size and count will not exceed specified limits. Documentation is required.

3. Test Guidelines

1) Conduct contamination susceptibility tests during development to determine the level of contaminant that the valve can tolerate.

2) To eliminate components with latent manufacturing defects, conduct 50 to 100 run-in cycles.

3) Do not rapid cycle valves designed for rapid applications for functional verification in a dry condition because the lack of fluid damping can increase seat stress and reduce life.

4) Conduct life cycle endurance tests under operational conditions. For long-life applications, the valve cycle life parameter must be known.

5) Require calibration logs be kept on pressure regulator assemblies to determine if the unit is drifting out of limits prior to service usage.

6) Test for corrosion of materials in the presence of the working fluid and the maximum expected impurities expected during operational life. Evaluate pitting and stress corrosion as well as penetration rates over a large surface area.

7) Consider use of holographic interferometry test methods for fluid compatibility evaluations. These methods allow evaluation of the onset and time variation of the corrosion process and permit three dimensional evaluation of localized effects.

8) After operational valve use, measure the response characteristics of the valve and perform trend analysis to identify wear trends.

9) Consider means to minimize cold flow during service. Initial analyses of an accelerated test for Teflon valve seat/poppet assemblies indicate that if the assembly is subjected to normal design loads and 150° C temperature for 14 days, then the assembly would not experience any more appreciable cold flow in a ten year period.

4. Application Guidelines

1) To avoid contamination and to prevent leakage, install components into systems using permanent connections, such as welded, brazed, or swaged connections rather than reconnectable mechanical joints.

2) Solenoid valves and pressure regulators are not normally repairable by in-flight maintenance procedures.

3) System design should identify the Line Replaceable Units (LRUs) consisting of individual valves or regulators, or groups of valves or regulators, for ease of remove/replace activities in the event of component malfunction.

4) A solution to reliability problems is the application of valves and regulators into redundant configurations.

I. GUIDELINES FOR THERMAL CONTROL VALVES

Service life estimates for thermal control valves (TCV's) used in fluid systems with internal temperature sensing ranged from 5000 hours to three years and from 8000 cycles to 20,000 cycles. The cycle life of TCV's used in fluid systems with external temperature sensing is 15,000 cycles (by test) and a three to five-year service life is obtainable. The TCV service life requirements cannot be met for long duration programs unless maintenance and restoration is permitted.

Listed in the order of most probable occurrence, the TCV failure modes are:

1) Failure to modulate flow within limits;

2) External leakage.

1. Design Guidelines

Due to the relatively short service life of current TCV designs it is suggested that:

1) TCVs be designed for both manual or automatic operation whether the temperature is sensed internally or externally; to provide additional flexibility in manned space vehicles;

2) The designer consider modular replacement ease;

3) Standby redundancy be used when the life limiting failure mode for a TCV is wearout.

4) Design large flow paths (areas) through thermal control valves and main sealing surfaces to reduce flow velocities and erosion of seats.

5) Configure housings (as far as possible) to eliminate areas that can entrap contaminants. Use a "swept by" design where flow will tend to pass contaminants through the component.

6) Insure that materials are compatible with the working fluid including maximum expected fluid impurities. The evaluation must consider dynamic as well as static applications and must consider temperature, pressure, and phase variations of the fluid.

7) Minimize component induced contamination:

   a. Material selection should consider the effect of wear particle size on useful life. Particle sizes vary as the Young's Modulus divided by the square of the compressive yield stress;

   b. Use rolled threads in preference to machined threads to minimize burrs and achieve higher strength;

   c. Minimize dead-end passages and capillary size passages.

8) Leaks due to contamination are minimized if the seat loads are sufficient to plastically yield a trapped contaminant particle on the sealing surface. System contaminants must be identified to determine particle size and material properties.

9) Avoid sliding parts; they not only induce contamination, but entrap contamination.

10) Develop valving elements with quick opening areas to preclude chattering, instability and high seat velocities.

11) Spherical or tapered poppets are recommended. These poppets are self-aligning, but require precise alignment of the seat and the poppet assembly.

12) Insure guiding of poppet onto seat to allow for maximum alignment and eccentricity tolerance (i.e., use a large length/diameter bearing surface to guide ratio - minimum 2:1).

13) High safety factors should be used in conjunction with high seat loads since low seat stresses are desirable for long life.

14) Lipseals supported with a back-up ring to resist undesirable influences of pressure loading are superior to designs without this provision. It is recommended that lipseals guiding piston rods or poppets use back-up sealing rings in addition to the main lipseal.

15) To minimize transient stresses due to poppet travel, provide positive stops at the end of travel.

16) Seal retention methods shall prevent seal distortion, creep or dislodgement.

17) Reduced life due to vibration sensitivity is minimized by decreasing available clearances in bearings and guides, avoiding large overhung moments, and restraining lateral motion of poppets.

18) Control stress corrosion by avoiding stress corrosion susceptible materials or design parts to operate at low stress levels.

19) Justify the use of dynamic seals. They are subject to wear and cause unpredictable drag.

20) Control external leakage by:

    a. Requiring welded valve body construction;

    b. Requiring vacuum melt bar stock;

    c. Impregnating valve casting with sealant.

21) The solenoid open and close force margin goal is 300%. Failure of the poppet to open (or close) may be caused by binding of the plunger or insufficient solenoid force.

22) Prevent insulation deterioration and subsequent solenoid shorts that can lead to reduction in electromagnetic force by:

    a. Coating solenoid valve lead wires with an abrasive resistance covering;

    b. Taking special precautions when joining the lead wire to the solenoid coil wire;

    c. Potting coils and lead wires to prevent movement during vibration and operation;

    d. Using wire gages less than 40.

2. <u>Process Control Guidelines</u>

1) Ultrasonically clean valve parts; assemble in specified level-clean areas, and govern by a single contamination control specification during test. This same control specification should also govern the test fluid media used.

2) Use a fabrication barrier (bag) to protect clean parts. Consider using nylon or polyethylene to prevent creation of contamination due to chaffing of the barrier by the parts.

3) Vendor controls shall guarantee that the valve contamination particle size and count will not exceed specified limits. Documentation is required.

3. Test Guidelines

1) Conduct contamination susceptibility tests during development to determine the level of contaminant that the valve can tolerate.

2) Perform 50 to 100 run-in cycles to eliminate components with latent manufacturing defects.

3) Do not rapid cycle valves for functional verification in a dry condition because the lack of fluid damping can increase seat stress and reduce life.

4) Conduct life cycle endurance tests under operational conditions. For long-life applications, the valve cycle life parameter must be known.

5) Test for corrosion of materials in the presence of the working fluid and the maximum expected impurities expected during operational life. Evaluate pitting and stress corrosion as well as penetration rates over a large surface area.

6) Consider use of holographic interferometry test methods for fluid compatibility evaluations. These methods allow evaluation of the onset and time variation of the corrosion process and permit three dimensional evaluation of localized effects.

7) After operational valve use, measure the response characteristics of the valve and perform trend analysis to identify wear trends.

8) Perform leak checks after valve use and subject data to trend analysis.

4. <u>Application Guidelines</u>

1) To avoid contamination and to prevent leakage, install components into systems using permanent connections, such as welded, brazed, or swaged connections rather than reconnectable joints.

2) The controller/actuator of a Type B valve can be readily replaced without interrupting coolant flow.

3) System design should identify the Line Replaceable Units (LRUs) consisting of individual valves or groups of valves for ease of remove/replace activities in the event of component malfunction.

4) A solution of long-life and reliability problems is the application of valves into standby redundant configuration.

J. GUIDELINES FOR PRESSURE VESSELS AND POSITIVE EXPULSION DEVICES

There are tank systems in existence that will perform successfully on a mission of up to 10 years duration. Care must be taken to fit the type of expulsion device best suited to the mission under consideration if a 10-year life is to be obtained. Tank failure modes which would prevent obtaining a 10-year service life are listed below in the order of their most probable occurrence:

1) Expulsion device leakage;

2) Leakage of the tank weld or leakage at fitting;

3) Tank rupture.

The estimated cycle lives of subject expulsion devices are as follows:

1) Convoluted, metal diaphragms are impermeable to propellant and work well for one expulsion. Severe metal working causes pinholing and failure, in most cases, when recycling is attempted.

2) Equatorially clamped, elastomeric diaphragms are good for 500 expulsion cycles with 99% expulsion efficiency.

3) Elastomeric and polymeric bladders, due to severe folding encountered during expulsion, have a cycle life limited to 30 to 35 cycles--shorter than elastomeric diaphragms lives, but longer than metal diaphragms lives.

4) Both metallic bellows and pistons are impermeable to propellants and both should function for more than 500 cycles.

5) Surface tension devices promise a life of at least 1000 cycles, many times longer than the other devices because they are immune to many of the failures that plague the other expulsion devices.

6) When exposed to corrosive fluids, the service lives of nonmetallic expulsion devices are less than three years due to permeation and incompatibility. The service life of metallic expulsion devices is greater than 10 years.

Table III-1 summarizes the relative merits and weaknesses of positive expulsion devices for use in long-life space missions.

1. Design Guidelines

1) For a 10-year mission, no design changes are necessary in any of the designs studied to compensate for radiation damage. Resistance of all the materials to radiation is high enough and expected radiation levels are low enough to eliminate radiation damage as a problem.

2) Metal tanks, which represent proven designs and materials, shall be used for long-life applications.

3) Fracture mechanics tests are required to describe the fracture of materials under static, cyclic, and prolonged stress loading conditions.

4) Spherical tanks are required--constraints permitting. Spherical tanks offer the following advantages; they are: lightest in weight, easiest to fabricate, and more reliable for long-life due to less welds.

5) Use metallic expulsion devices, mission constraints permitting. They remain relatively unaffected when exposed to corrosive fluids.

6) Surface tension and metallic bellow devices have demonstrated characteristics which are consistent with long-life space applications. Surface tension devices are highly rated because they have no moving parts. Bellows are rated good because of past reliable performances.

7) The various methods of attaching the expulsion device to the inner tank wall do not present a problem for long space missions.

8) Use folding controls, such as masts or spring attachments on expulsion devices that exhibit potential problems with folding, ripping, and tearing failures.

2. Process Control Guidlines

1) Provide documented controls to assure handling and shipping care. Thin walled screened devices, metallic diaphragms, and bellows are structurally delicate.

2) Contamination controls for screened devices are necessary to obtain uniform operational characteristics from tank to tank. Require that vendors submit for approval contamination controls and methods of implementation for screened devices.

3) Several tank users recommended that tanks be stored with an inert blanket pressure in an inert atmosphere for contamination considerations and the prevention of material corrosion.

3. Test Guidelines

1) To verify operational usage, tank selection criteria should advocate expulsion devices (elastomeric diaphragms and metallic bellows) for which positive tests can be performed.

2) Use radiography and dye penetrant test methods to verify the integrity of tank welds.

3) Conduct various combinations of propellant/elastomer exposure tests to develop long term compatibility. Ten year test data are not available.

4. Application Guidelines

1) As compared to other parts and components, tanks have a relatively low sensitivity to the manner in which they are applied in a subsystem. However, because of the crew safety element and the inherent failure mode of explosion, all design, manufacturing, and testing plans and activities must be very closely controlled.

2) In manned spacecraft, locate pressure vessels to minimize crew risks in event of an explosion.

Table III-1 Relative Merits and Weaknesses of Expulsion Devices for Use in Long-Life Space Missions (Up to 10 Years)

PARAMETER	BLADDERS	ELASTOMER DIAPHRAGMS	METAL DIAPHRAGMS
Cycle Life	Metallic 1 cycle elastomer <35	50 to 500	1
Calendar Life (exposed to propellant)	30 days to 3 years for elastomer; 10 to 15 years for metallic bladders	30 days to 3 years	10 to 15 years
Resistance to Radiation	Good in absence of oxygen	Good, no problems	Good, no problems
Attachment Problems	Strain on neck during slosh at neck flange	Equatorial clamping device very stable	Equatorial weld and clamping device very stable
Movement Failures (Folding, Tearing, etc.)	Severe folding causes tearing, pinholing, etc.	Slosh and expulsion may cause slight wear	Pinholing and tearing certain after first cycle
Permeability to Propellants	Severe problems with may propellants, especially N_2O_4	Problems with several propellants, again N_2O_4	Impermeable during first expulsion cycle
Compatibility with Propellants	Swelling followed by permeation	With new elastomers (Martin Marietta EPR 132), very little swelling (under 3%), some propellant breakdown	No problem when correct metal is used
Suitability for a 10-year Space Mission	Metallic bladders are unsuitable due to their limited cycle life and elastomer bladders are not suitable due to their life when exposed to propellants.	Elastomer diaphragms are not suitable for long life due to their limited life when exposed to propellants. The problem with elastomers is not necessarily that the elastomer degrades (EPT-10, for example, looks promising after several months exposure to N_2H_4) but that 10 year test data are just not available.	Unsuitable for more than 1 cycle

Table III-1 (cont)

PARAMETER	PISTONS	METALLIC BELLOWS	SURFACE TENSION DEVICES
Cycle Life	>500	>500	>1000
Calender Life (Exposed to propellant)	To 3 years due to seals	10 to 15 years	10 to 15 years
Resistance to Radiation	Good	Good	Good, no problems
Attachment Problems	Pistons are held against the fluid by gas pressure or mechanical actuation device	Current applications have been limited to approximately two feet in diameter	Tight fit inside tank, very stable
Movement Failures (Folding, Tearing, etc.)	Non-metallic seals could wear or shred - metal seals could cause high breakaway function and wear	Metal crack and pinhole leaks	Not applicable
Permeability to Propellants	Elastomer seals are permeable to propellants	Impermeable	Control flow rate, pressurant gas can dissolve or become saturated in propellants.
Compatibility with Propellants	Teflon seals will swell when exposed to N_2O_4	No problems	No problem if correct metal can be fabricated into a screen
Suitability for a 10-year Space Mission	Metallic seals are suitable for a 10 year life; Elastomer seals are not suitable due to their life when exposed to propellants	Suitable for a 10 year life	Suitable for a 10 year life

K. GUIDELINES FOR Ni-Cd BATTERIES

A shallow depth of discharge, limited overcharge and recharge rates, and low temperature are necessary for a long life battery. The average service life of a Ni-Cd battery can approach five years and/or at least 7000 charge/discharge cycles. Twenty thousand cycles can probably be obtained. These estimates are for depth of discharge cycles not exceeding 25% of rated capacity and a battery temperature not exceeding 21.1°C. Ni-Cd batteries can be stored for over five years if stored discharged, shorted and about 0°C. Separators are the primary life-limiting elements of the battery.

1. Design Guidelines

1) Design excess capacity into the battery to reduce the percent depth of discharge and compensate for capacity decrease with usage. The penalty is cost and watt-hours/pound.

2) The negative to positive plate area ratio should be at least 1.5:1 so that the negative plate area can absorb the oxygen generated during recharging, preventing battery overpressure;

3) Use non-woven polyproplene separators since they degrade slower than nylon at higher temperatures. The non-woven configuration wets more readily;

4) Hermetically seal the battery to avoid degradation of other spacecraft parts by the electrolyte in unmanned missions;

5) Either plate the terminal seal braze with nickel or consider using a nickel-titanium braze material to reduce the probability of electrolyte attacking materials containing copper;

6) Employ a pressure relief valve (200 psi or less setting) for batteries used in manned missions to prevent crew injury in case of battery overpressure. Provide backup monitoring of the battery to terminate/reduce the charge should the primary system fail. Replace battery if pressure relieved because chemical balance is upset and cell case probably distorted.

7) Use 304 or 304L stainless steel for case and cover material. These materials have proven satisfactory;

8) Use ceramic to metal terminal seals that are more KOH resistant than glass.

2. Process Control Guidelines

1) Employ clean areas during processing and manufacturing to reduce the amount of harmful contaminants. Also, use clean lint-free cotton gloves when handling components. Store components in clean plastic bags when not being processed;

2) Employ clean processes, remove the carbonates and keep the nitrates content down to prevent gas pockets that pop off active material;

3) Flush plates after KOH is used in the process to form active hydroxides to remove carbonates;

4) Flush and brush plates prior to installation to remove contaminants;

5) Coin plates flat. Flex and clean plates prior to assembly. Have resident inspector examine plates for conformity just prior to cell assembly. These actions will reduce the probability of short due to projection of jagged wire filament through the separator, loose particles of plate material and tab failures;

6) Weigh each plate to be certain weights are within ±3½% of mean. Also, perform actual capacitance measurements to check plate matching. Mismatched cells can prevent full battery charge;

7) Control the brazing temperature-time relationship to prevent excess dwell during brazing operations that can cause active material penetration of ceramic seals;

8) Avoid rapid cooling after brazing to prevent cracked ceramics and brazing voids.

9) Purge cells of air prior to injecting electrolyte to prevent KOH reacting with CO_2 to form carbonates;

10) Place plates under serialized control and provide traceability for separators and electrolyte material to improve the quality of individual cells which has varied more than desired;

11) Require process and test controls for each active element--plates, separators and electrolyte to reduce end product variability.

3. Test Guidelines

1) Helium leak check the assembled cells. As an alternative, conduct a check with phenolphtalein;

2) Subject battery during acceptance test to a minimum of three charge/discharge cycles, high impedance short test, and leakage tests. These tests should provide assurance that the basic operating characteristics and construction are satisfactory;

3) X-ray along three axes to find gross battery defects.

4) Conduct a minimum of 30 charge/discharge cycles on assembled cells to minimize infant mortality and to confirm the matching of individual cells. Resident inspection should observe and confirm these tests.

4. Application Guidelines

1) Maintain battery within a -20°C to +22°C temperature range to retard separator deterioration;

2) Keep depth of discharge below 25% of rated capacity to assure a longer life;

3) Limit recharge and overcharge as denoted below to assure longer battery life.

   a) The recharging rates should be limited to the range of C/2 to C/10. (C = rated capacity in ampere-hours)

   b) The overcharge should be limited to:

      105% C @ 0°C
      115% C @ 25°C
      125% C @ 40°C

4) Plan to replace batteries operating under favorable usage and environments every five years (if feasible) - their maximum estimated life.

5) Store Ni-Cd batteries at approximately 0°C in a discharged and shorted condition to obtain a storage life of about five years.

6) Monitor individual cell voltages for indications of cell deterioration and potential replacement requirements.

7) Erase most memory by discharging battery, short for 16 hours, and then recharge if application permits and need arises. Repeated shallow depths of discharge can prevent future fuller depths of discharge ("memory").

L. GUIDELINES FOR TRANSDUCERS

Selected pressure and temperature transducers are capable of life in excess of 10 years. Flow meters have less life capability, but meters without moving parts and operating in an environment of low contamination and corrosion are capable of long-life. Humidity, oxygen and carbon dioxide sensors are life limited, requiring periodic maintenance actions such as cleaning, and replacement of cartridges.

A prime problem with transducers is the lack of long-term stability (freedom from drift). The solution to this problem lies in making the total transducer dimensionally stable over long periods of time. Accordingly, it is important to minimize the use of non-metallic materials and to employ and control processes that yield parts in a stress free condition. Long term stability (and process control) must then be demonstrated through testing of the assembled transducer under appropriate environment conditions such as temperature cycling.

A well-constructed test program provides the best assurance that a transducer will perform satisfactorily in a long-life application. Unfortunately, the lead time available from selection of a transducer to commitment of the transducer to service may be only a fraction of time required for a comprehensive test program. Therefore, transducers should be chosen where such data has already been acquired.

Long-life transducer applications fall into two broad classifications: open-loop and closed-loop. Open-loop applications only provide information regarding the performance of a system. Closed-loop applications involve a control function to regulate a system based upon transducer output. Transducer failures in open-loop applications result in uncertainty about the condition of the system, while similar failures in closed-loop applications result in failure of the system. Consequently, closed-loop applications of transducers are more critical from the standpoint of failure effects. They require greater attention to the factors influencing reliability and life.

In general, redundancy techniques do not provide solutions to transducer problems. Active redundancy cannot provide a solution if a known life limiting mechanism exists in the transducer. Multiple potentiometer wipers, exposed to the same wear, may fail within the same time span. Stand-by redundancy is generally not feasible.

In standby redundance a non-active transducer is protected from the failure producing condition until the first transducer has failed. Applications involving stand-by redundance are severely restricted by size/weight and the complexity of devices required to switch from the active to the stand-by transducer.

1. General Transducer Guidelines

1) Procurement specifications should be tailored to permit the use of existing designs with proven long-term stability and in current production. Even minor changes to a proven device may invalidate its long-term stability and reliability. Exceptions to this rule should be held to the absolute minimum.

2) A basic cause of problems has been poor technical communication between the manufacturer and the procuring agency with non-technical people in the loop, such as procurement personnel and sales representatives. Timely and efficient communication on technical requirements and problems must be achieved to insure a reliable product.

3) Use hermetically sealed, welded case designs. These are available with almost all types of transducers and are preferred for long-life applications.

4) Designs which eliminate or minimize the use of non-metallic materials are preferred. With many transducers, the creep and/or deterioration of internal non-metallic materials, such as epoxy bonding agents, is a primary life limiting factor. An example of a design approach which eliminates all non-metals is the thin film strain gage pressure transducer.

5) The basic design should minimize stress-induced creep. During manufacturing, annealing processes should be used to further reduce the internal stresses which produce creep and calibration shifts. With many transducers, the creep of metal parts under stress causes calibration shifts.

6) Transducers for long-life applications should be selected, wherever possible, only when long-term, or valid accelerated test data is already available to provide proof of long-term stability.

7) Employ transducers based on simple operating principles and no moving parts since they provide the best promise for long-life applications. Bearing, pivots, gears, and sliders may all be required in a high-performance, high-resolution transducer;

however, the life of such devices will be limited. To achieve long-life, transducer performance may sometimes have to be sacrificed in favor of simplicity.

8) In selecting a specific transducer, the complexity of the associated electronics is frequently the primary threat to long-life, and this factor should be strongly weighted.

9) The electronics associated with transducers should be fabricated using screened Hi-Rel parts. If this is not affordable, screening the electronics at the component level using temperature cycling is recommended.

10) Variables introduced in manufacture and assembly of a transducer must be controlled if long-life is to be achieved. Historical data indicate that many transducer failures can be attributed to poor process control, poor workmanship, and inadequate quality control. Poor solder joints and introduction of moisture and other contaminants during manufacture have been problems.

11) The larger devices are usually preferable for long-life and reliability. They are generally more rugged and less sensitive to manufacturing process deviations. Attempts to miniaturize a proven transducer design often compounds workmanship and process control problems.

2. Specific Transducer Guidelines

a. Temperature Transducers

1) Platinum wire resistance sensors are preferred for long-life applications. The wire must be of high purity and wound in a manner to minimize mechanical strain.

2) Avoid the use of thermocouples coupled with hi-gain amplifiers because of the problem of thermal instability. Thermocouples are best suited for high temperature measurements.

3) Some thermistors, depending on the specific manufaturer, are subject to drift. Such devices should be stabilized by a 1000-hour burn-in at 150°C.

4) Quartz crystals provide very stable performance, but the complexity of the associated electronics creates a greater chance of random failure.

5) The use of sensistors should be limited to circuit compensation applications because they lack stability as temperature sensors.

6) Life, reliability, and stability should be demonstrated by accelerated temperature cycling with the temperature range and the number of cycles exceeding the projected use conditions.

b. Pressure Transducers

1) The diaphragm should be designed to operate at less than 50% yield to achieve a life of 10^6 cycles.

2) Pressure transducers should be designed with a burst-to-operating pressure margin of 250% minimum to minimize the risk of case rupture.

3) Over-pressure stops should be designed into the transducer to prevent damage to the diaphragm when exposed to pressure surges or transients.

4) The bonding of strain gages is critical because creep of the epoxy will cause drift. Designs which eliminate non-metallic materials are preferred for long-life applications.

5) Potentiometric transducers are not the preferred choice either for long-life applications or for stringent vibration and shock applications because they are susceptible to noise and wear from wiper dither in localized segments of the resistive element.

6) Absolute pressure transducer designs which eliminate feed-through wires into the reference cavity are preferred since they eliminate potential leak paths. Cleaning and sealing of the reference cavity is critical.

7) Pressure transducers should be stabilized by 5 to 20 temperature cycles, depending on the accuracy requirements.

c. Humidity

1) The dew point hygrometer should be limited to applications in which scheduled maintenance is available. The sensing mirror is susceptible to contamination and should be accessible for periodic cleaning.

2) Aluminum oxide hydrometers are not recommended where accuracy and long-term stability are required. Simplicity of the device is offset by its susceptibility to poisoning (and drift) by atmospheric contaminants.

3) Quartz crystal hydrometers with solid sorbents are suited to applications requiring high sensitivity and stability over a wide range of relative humidity.

d. *Flow Meters*

1) Head-type and thermally sensitive meters are sensitive to fluid temperature and require compensation to permit accurate measurement over a wide temperature range.

2) Head-type meters are susceptible to calibration drift resulting from orifice contamination and should be protected with filters in the fluid line.

3) Heat-type meters should be of all welded construction and designed for 250% overpressure to minimize the risk of case rupture.

4) Thermally sensitive meters should be avoided in rapid response applications involving stringent shock and vibration environments. Heater and thermocouple of elements in these meters are fragile and susceptible to damage.

5) Volumetric turbine meters should be restricted to applications in which steady flow is anticipated and fluid temperature is maintained within narrow limits. Thermal expansion of the meter turbine and housing will result in wear, internal leakage, and loss of accuracy.

6) Magnetic flow meters contain no moving parts susceptible to wear and require no obstruction in the fluid stream. They are preferred in applications where maintenance is permitted without disturbing fluid lines.

e. *Oxygen/Carbon Dioxide Sensors*

1) Except for the electrochemical cell, the complexity of instruments available for sensing oxygen or carbon dioxide does not warrant their use in long-term, unattended applications. These instruments include mass spectrometers, infra-red analyzers, ion chambers, spectrophotometers and chromatographs.

2) Electrochemical cell sensors are preferred in applications requiring long-term stability without calibration for 1000 hours.

IV. LONG-LIFE ASSURANCE GUIDELINES FROM THE SPECIAL STUDIES OF VOLUME IV

A. GUIDELINES FOR TEMPERATURE CYCLING AS EMPLOYED IN THE PRODUCTION ACCEPTANCE TESTING OF ELECTRONIC ASSEMBLIES ("BLACK BOXES")

Temperature cycling, as an acceptance test of production assemblies, is widely used as a test screen for the detection of workmanship and parts defects at the "black box" level. It also reveals design deficiencies when it is not extensively employed during development and qualification testing. It is usually used in conjunction with vibration. It is combined with vacuum exposure when appropriate, and it is particularly applicable to electronic equipment.

Examples of the types of defects screened out by temperature cycling are:

Faulty capacitors, transistors, diodes, integrated circuits, etc.
Shorts and opens in transformers and coils.
Faulty solder and weld joints.
Shorts in cabling.
Faulty insulation washers, lugs shorted to ground, etc.
Defects in printed circuit boards.
Problems due to incorrectly applied conformal coating.
Drift problems.
Failures of plastic-encapsulated parts.
Defective potentiometers, relays, etc.
Improper staking of tubing coil slugs.

<u>Guidelines</u>

1) A survey of 26 companies/agencies shows that the preponderance of opinion is that more than one thermal cycle is required.

2) Test data from seven companies shows that 6 to 10 cycles are required for the elimination of the incipient defects. Six cycles appear adequate for black boxes of about 2000 parts, while 10 cycles are recommended for equipment containing 4000 or more parts.

3) The following companies subscribe to 6 to 10 cycles: Martin Marietta Aerospace, General Electric, TRW, Lockheed, Collins Radio, Radiation Incorporated, and Aerospace Corporation.

4) Hughes Aircraft Company has developed mathematical models to predict how many cycles are required to achieve a specified reliability depending on the previous amount of screening,

the quality of parts used, and the exact thermal conditions and profile for the parts being screened. Many more than 10 cycles are sometimes required, per their model.

5) When unscreened parts are used and temperature cycling of assemblies is employed as the main production screen, more than 10 cycles may be required. Programs of 16 to 25 cycles have been used.

6) Temperature ranges of -65°F to 131°F are the temperatures most commonly used. Most parts will withstand temperature cycling with power off through a temperature range of -65°F to 230°F. Heat rise with power on under test cooling conditions should be calculated to limit the chamber temperature to a maximum safe value. The maximum safe range of component temperature and the fastest time rate of change of hardware temperatures will provide the best screening.

7) The rate of temperature change of the individual electronic parts depends on the chambers used, the size and mass of the hardware, and whether the equipment covers are taken off. In general, the rate of change of internal parts should fall within 1°F per minute and 40°F per minute, with the higher rates providing the best screening. A temperature range between 160°F and 225°F is recommended.

8) Temperature cycling with good parts and packaging techniques is not degrading even with several hundred cycles. However, the packaging design must be compatible with the temperature cycling program or the acceptance test yield will be reduced (to zero in some special cases). This compatibility is established by temperature cycling the pre-production hardware.

9) The equipment should be closely monitored during the operating portions of the cycle. It is desirable to turn off the equipment during chamber cool-down or self-generated heat will prevent the internal parts from reaching the desired low temperature.

10) When multiple temperature cycling is used as an acceptance test, it is standard practice to allow repairs without requiring a repeat of the entire test. Some programs permit failures during cycling, some have required the two final cycles to be failure free, and one program (involving very simple hardware) required 20 consecutive failure free

cycles. It is recommended that one final failure free cycle be required, together with criteria for extending the number of temperature cycles as a function of the difficulty and magnitude of the repair.

11) Implementing temperature cycling is most compatible with PC board construction and least compatible with large, complex, potted cordwood modules where failure means scrapping the entire module.

12) The concept of augmenting the black box temperature cycling with additional cycling at the PC board level should be considered. Hughes Aircraft, on one program, "stores" their assembled PC boards in a temperature chamber for one week during which time 158 temperature cycles are accrued. The boards are not powered or monitored. This comprises a very cost-effective approach to reliability.

13) An approximation of the types of failures detected in mature hardware by temperature cycling is:

Design Marginalities	- 5%
Workmanship Errors	- 33%
Faulty Parts	- 62%

14) Much of the data in this report is derived from programs using AGREE testing per MIL-STD-781B. The AGREE cycle combines temperature ramps, temperature soaks, and low level (2g) vibration. The concensus is that the temperature soaks and the low level vibration play a very minor role and, therefore, the AGREE technique is essentially equivalent to a temperature cycling test, with the screening strength of the test dependent on the temperature range, the temperature rate of change, and the number of cycles.

15) The packaging design must be compatible with the temperature cycling program or the acceptance test yield will be reduced. Some situations in which electronic hardware may be adversely affected by temperature cycling are listed below.

    a) Solder joints may crack due to inadequate stress relief. One typical problem is the problem with conformally coated transistor cans on spacers when lead stress relief is not provided. This situation also occurs in relays, transformers, and large modules when the studs or pins are soldered into printed circuit boards without provisions for stress relief of the solder joint.

b) Thick applications or heavy fillets of conformal coating can break or damage parts and solder joints. Bridging of conformal coating under flat-bottomed parts is particularly catastrophic and must be avoided.

c) The use of an encapsulating compound with a high modulus of elasticity and high coefficient of thermal expansion may damage parts and connections.

d) Weak parts, such as glass diodes, must be protected by sleeves before applying conformal coating.

e) Plastic-encapsulated parts are frequently a problem in a temperature cycling environment, because of stresses from thermal expansion incompatibilities.

f) Multilayer printed circuit boards may fail by cracking at the plated-through holes if the hole plating is too thin or is not ductile, or if the holes have not been cleaned prior to plating.

The above situations can all be avoided by using good parts and proper packaging techniques, and by using temperature cycling to verify the packaging configuration. See "Electronic Packaging" in Volume II.

In general, electronic parts are not subject to significant degradation from temperature cycling, but there are always exceptions. A recent problem was encountered with a photodiode in which the internal construction contained fine wires encapsulated in epoxy: failures resulted because the metal and plastic had incompatible thermal expansion characteristics.

Extensive investigations by the NASA-MSFC Solder Committee concluded that any good solder joint can tolerate 200 severe temperature cycles from -67°F (-55°C) to 212°F (100°C) without evidence of the start of cracking.

Investigations by RADC and IBM place the state-of-the art of good multilayer printed circuit boards at between 200 and 1000 temperature cycles.

16) On programs desiring to utilize off-the-shelf hardware which does not contain Hi-Rel parts, and where cost considerations prevent the substitution of Hi-Rel parts, temperature cycling is a lower cost alternative for reliability improvement. For hardware not containing Hi-Rel parts, Radiation Inc. recommends 16 to 25 cycles and has employed as many as 32 cycles.

B. GUIDELINES FOR ACCELERATED TESTING

Quantitative accelerated test techniques have been developed for very simple parts and for materials. For more complex devices containing multiple failure mechanisms, each mechanism usually has a different, and non-linear acceleration factor; valid quantitative methods neither currently exist nor are they apt to be developed in the foreseeable future. This category includes electronic assemblies, batteries, bearings, valves, transducers, and other electromechanical hardware. However, reliable qualitative accelerated test methods exist; and these methods merit continued development and application in programs requiring long-life. Past history has shown that qualitative accelerated life test techniques have produced hardware with increased life and reliability, even though they do not provide a quantitative life assessment.

These guidelines present a concise summary of the state-of-the-art, describe current research, and identify those techniques which should be further encouraged.

1) <u>Non-metallic Materials</u>

The use of the Thermogravimetric Analyses technique can yield significant schedule and cost savings as a partial cost-effective substitute for real-time, long duration, thermal vacuum testing. This technique is currently being developed by Martin Marietta Aerospace.

2) <u>Solder Joints</u>

Every long-life spacecraft program should verify the integrity of solder joint configurations by extensive temperature cycling beginning with the earliest prototypes. This is usually accomplished in an ambient air temperature chamber, using a nominal cycle of about one hour. A two-minute cycle consisting of immersion in cold and hot liquids is about three times as severe and yields a test program time reduction of 90. This is very attractive, when the temperature cycling program requires thousands of cycles, as was the case with the Apollo Telescope Mount Gyro Precessor.

3) <u>Electronic Parts</u>

Electronic part accelerated test techniques are more advanced than other part types. It can be effectively utilized on semiconductors, resistors, and capacitors. Step stress and high temperature constant-stress tests, utilizing the Arrhenius model, are recommended as the most advanced approach for semiconductors. Further development of techniques is required for complex devices such as LSI/MSI. The inverse power rule and progressive stress or constant stress tests are the recommended approach for capacitors. It is not necessary to perform accelerated tests to obtain quantitative data such as failure or hazard rates. Simple qualitative tests can provide conservative life estimates, margin information, and data for comparative evaluations or estimating screen level effectiveness. Accelerated testing can be applied effectively when such data is needed. It is recommended that these approaches be used selectively as these requirements arise, as opposed to imposing a general accelerated test requirement on a program.

The temperature and power screening levels imposed by Bell Telephone Laboratories on discrete semiconductors and integrated circuits for high reliability applications are much higher than generally used in the industry. The commonly used levels and durations are almost benign by comparison. These high levels were derived through experience with accelerated testing that indicates the commonly used levels may not be the most effective. It is recommended that further studies be made to examine the feasibility and desirability of implementing higher temperature screening (burn-in) levels on selected parts.

4) Electronic Assemblies

Both multiple temperature cycling and AGREE (MIL-STD-781B) testing are very powerful forcing functions for improving the reliability of electronic assemblies. Their wider use in development, qualification and production acceptance testing should be encouraged. Temperature cycling is less costly to implement than AGREE because of the contractual risks of AGREE testing to the producer; but AGREE testing should be considered for wider use by NASA, particularly on the larger procurements where its application becomes more cost-effective. Based on an industry survey of 26 companies, both methods were more effective than constant temperature burn-in.

Step-stress testing to failure by progressively increasing the temperature, as developed by Grumman, should also be considered as a good development tool to detect and rectify weak links.

Although this technique has no application in qualification or production acceptance testing, it is considered an excellent development test technique.

5) Mechanical/Electromechanical Hardware

Accelerated test approaches are not developed or utilized to the extent existing for materials, solder joints, electronic parts, and electronic assemblies.

6) Batteries

Valid quantitative accelerated life test techniques have not been developed for batteries. Current investigations at the Naval Ammunition Depot and at Battelle Memorial Institute should be monitored, but a significant state-of-the-art breakthrough is not anticipated. The allocation of additional resources is not recommended. Qualitative approaches, by increasing the temperature and depth of discharge, have application in battery development programs to understand the failure mechanisms, since the data can be utilized for design improvements.

7) Bearings

Valid quantitative accelerated life test techniques have not been developed. However, further efforts should not be discouraged since every attempt yields additional data and insight into failure mechanisms. It appears feasible, according to LaRC bearing experts, to accelerate a life test by increasing the temperature, when the bearing is designed to operate in the elastrohydrodynamic lubrication regime. Long-life bearings should be designed wherever possible, to operate in this regime.

Recent developments in bearing technology have shown that a previous method of accelerating life by increasing the radial load is invalid.

Some so-called accelerated life tests on bearings are not true accelerated tests, but are efforts to extrapolate measured real-time degradation out to a life prediction. These techniques provide a rather inaccurate prediction. But they do serve to provide the bearing technologists with valuable data that is used to extend the life of bearings, even though a valid quantitative life prediction is not achieved.

For the bearings in the future reusable space vehicles, the issue of designing bearings to withstand many repeated exposures to severe vibration without reduction of life due to fretting corrosion (false brinelling) becomes paramount. Economic resources should be directed towards the solution of this problem.

8) Valves

Increasing the cycling rate of valves is a valid accelerated test approach when long-term aging mechanisms are either not present or have been designed out. When aging phenomena is present, then the increased cycling rate approach must be augmented by other accelerated test programs. Examples of aging phenomena are corrosion by fluids, cold flow of teflon seats, and bonding of a metal seat to a metal poppet due to metal diffusion. A current program being conducted by TRW for JPL on the diffusion problem and on acoustic signature testing is of interest.

The development of acoustic signature testing is being pursued by both TRW and GE. This technique will not provide a true accelerated test, but it has the potential of identifying degradation within the valve due to wear or aging. These trends could be extrapolated to a prediction of life. This technique is usually inaccurate since the amount of degradation necessary to cause failure is difficult to accurately establish.

In general, valve specialists consider accelerated testing to be untrustworthy; but utilize it in the absence of a valid, quantitative technique. As with bearings and batteries, every attempt to develop a valid method yields reliable information for improving the product, even though an accurate quantitative life estimate is not achieved.

9) Transducers

The principal long-life problem with transducers is not wear-out, but long-term stability (calibration shift). For existing devices which have proven stability based on months of real-time test data, there is little need for accelerated approaches. For newly developed devices, each specific design should be analyzed for the potential application of accelerated test techniques. For example, experience at Martin Marietta Aerospace has shown that a minimum of five temperature cycles, exceeding use levels by 30°F, are desirable to guarantee long-term stability. For very long-life programs, 20 temperature cycles are recommended.

10) <u>Enhanced Defect Testing</u>

In certain instances, this type of testing can quickly yield valuable data, although it is not strictly classifiable as accelerated testing. An example of its use is a program by IBM in which Multilayer Printed Circuit Boards were fabricated with a number of controlled defects and then temperature cycled to failure. This program quickly revealed that the ductility of the copper was the most important factor for long-life.

11) <u>Dynamic Mission Equivalent Testing</u>

This technique, developed by JPL, is applicable as a systems level spacecraft test. The test acceleration is achieved, not by the use of increased stress levels, but by operating the spacecraft hardware to simulate one or many actual missions, except that the non-operating, or quiescent periods are omitted. Since this testing does not cope with dormant aging phenomena, the DME program must be augmented by other accelerated test programs which address the specific dormant aging problems.

C. GUIDELINES FOR ELECTRONIC PART SCREENING

Specific recommendations on screening are presented in the individual studies of Volumes II and III. The purpose of this study was to review the overall subject of screening with particular attention to the unconventional screening techniques.

The effectiveness of screening tests currently performed on electronic parts can be partially measured by the quantity of defectives which are passing these tests and which show up later during hardware fabrication, test, or usage. The usual screen tests such as parameter measurements, thermal and mechanical shock, vibration, radiography, hermiticity, constant acceleration, etc., have evolved, over the years as methods to detect basic defects caused by material or process anomalies during manufacture. When a defect is encountered, often the user will generate another screen by adding a test to the procurement specification to prevent future occurrences. The screens being utilized on the common electronic parts are fairly standardized for many of the tests both as to type and to levels or durations. The tendency is to add new tests while retaining existing ones.

In addition to eliminating the more obvious defectives (screening out unreliable devices), more subtle screens have been attempted to further identify (within the remaining "good" devices of a lot) those items which have the probability of longest life. The perfect set of screen tests would positively eliminate all defective parts and precisely predict the operating life of each acceptable part with minimum time and cost expenditures. The guidelines developed from the screening study are shown below.

1) The most significant reliability problem common to most electronic part types is that of ionic and/or particulate contamination. This problem is significant for transistors, diodes, resistors, integrated circuits, relays, and switches.

2) Conventional screens are not adequate to detect and eliminate all contaminated parts. Further, some of the screens may degrade ionic contaminated parts to a condition where failure is potentially imminent in service life.

3) Other prevalent part defects inadequately detected by conventional screens are semiconductor bonds with heel cracks, integrated circuit microcracks at contact windows, and seal leaks of wet tantalum capacitors. These defects may also be advanced by conventional screens such that failure could be potentially imminent in early service life.

4) Conventional screens are oriented to elimination of parts with specific defects or weaknesses. In general, conventional screens are not designed either to screen out parts on the basis of life expectancy or to provide information regarding longevity of the parts being screened. It is strongly recommended that the high stress screen approach, such as that performed by BTL Laboratories be considered for application in future NASA programs.

5) The degradation analysis approach and step stress or constant stress testing to destruction are the most feasible techniques to obtain cost and time effective information on relative life expectancy of individual parts or longevity estimates of part lots.

6) The Linear Discriminant Analysis approach is not considered appropriate in real-time, real-cost programs. The method is too uncertain, purely statistical, and unrelated to physical kinetics. The one advantage it has is that there is no other linear combination of parameters which will provide a better "zero-time" screen.

7) Current-noise testing is not an efficient screen test if the noise index is used as a reject criteria. It is recommended that this approach be utilized only for detecting mavericks in a production lot, such that parts which have outlier noise levels are considered reliability risks.

8) Third harmonic analysis screening is unsuitable for semiconductors. Further study is needed to determine its efficiency on discrete linear devices. It may be more efficient than current-noise testing. At worst, it may also be useful to detect mavericks by means of outlier harmonic content.

9) Short-time overload tests in the order of 1 to 2 hours are potentially one of the most effective ways to screen resistors. It can probably replace burn-in and power conditioning tests. Elimination of burn-in should not be made without data establishing the maximum overload temperature required and the optimum duration.

10) Of the unconventional screen tests, neutron radiography has potential in inspection for contamination, particularly for switches, relays and circuit breakers. It may be useful on capacitors but should not be used on semiconductors containing boron dopant. The newer particulate contaminate tests

such as combined shock and vibration are promising but not 100% effective. Laser scanning is a promising and needed tool for probeless testing of integrated circuits, particularly bipolars. Other approaches such as electron beam probing is required for MOS circuits. The automatic visual inspection techniques, although highly desirable, need considerable development effort before being feasible.

D. GUIDELINES FOR DERATING AND GOOD DESIGN PRACTICE

1) The derating practices of the following space programs were reviewed:

Program	Agency
Pioneer	Ames Research Center
Pioneer, 777, Vela	TRW
ATS	Philco-Ford
Skynet	Philco-Ford
Skylab	Martin Marietta
Mariner	Jet Propulsion Lab
PPL II	Goddard Space Flight Center
Intelsat	Hughes
Spacecraft Policy	Grumman
Shuttle (preliminary)	Marshall Space Flight Center
Skylab	Manned Spacecraft Center

It was concluded that the MSFC policy as described in MSFC Specification 85M03936, dated 6 March 1972, represented the most consistent and balanced approach among the policies studied.

Because of the length and detail of the derating guidelines, the reader is referred to Chapter V of Volume IV for the detailed guidelines.

2) Part derating is one aspect of a conservative design approach to improve reliability. Although it provides increased safety margins, reduces the probability of catastrophic failure, and increases the time to achieve degradation levels, each particular circuit will have a different tolerance to part drift which is a function of lifetime, complexity, application, and failure criticality. The user must consider all aspects of his application and utilize all additional practices which will tolerate degradation and enhance success.

Therefore, Chapter V, Volume IV, also includes Design Practice guidelines which are recommended for use in conjunction with the derating guidelines to achieve reliable circuit design. Design Practice guidelines are presented for:

Worst Case Analyses

Transient and Power Sequence Protection

Grounding

Test Points

Shielding and Isolation

Analog Circuit Design

Pulse, Logic, and Low Level Switching Circuit Design

Power Switching Circuit Design

Power Supplies

Capacitors

Resistors

Transistors

Diodes

Transformers, and

Relays

E. GUIDELINES FOR VIBRATION LIFE EXTENSION OF PRINTED CIRCUIT BOARD ASSEMBLIES

In the Space Shuttle Program, which will require Vibration Qualification Tests of very long duration, possibly 28 hours, the principal problem with most electronic equipment is failure of the electronic part leads due to flexure of the PC boards at their resonant frequency.

The tests summarized in Chapter VI, Volume IV indicate that well-designed PC board assemblies, adequately damped, can survive 28 hours vibration at levels under 15 or 20 g rms at the spectrum chosen to be representative of the Shuttle Orbiter.

The tests show that edge clamping, the use of damping strips, and conformal coating reduced the amplification from 80 to 15 and very significantly extend vibration life. Two boards of different design, but not edge clamped, damped or conformally coated, were vibrated at 17 g rms. The amplification was 80 and lead breakage began at 26.5 hours and 13 hours. When the vibration level was increased to 34 g rms to accelerate the test, lead breakage began at 28 minutes and 20 minutes. However, when a board was conformally coated, and damping strips applied, the amplification was reduced to 35; the first failure at 34 g's was delayed to 2.5 hours. When this configuration was also rigidly clamped at the edges, the amplification was further reduced to 15; and no failures had yet occurred when the test was terminated at 5 hours, 40 minutes.

The vibration time acceleration factors obtained by increasing the vibration level 6 db were highly variable, varying from 1.5 to greater than 79. The mean of nine data points was 23.6. Although the scope of this test program was not sufficient to substantiate an accurate acceleration factor, the approach used could yield more valid acceleration factors by applying the approach to a greater number of hardware items. If the resulting acceleration factor was, for example 20, then a 28-hour test could be conducted in 1.4 hours by increasing the qualification test level by 6 db.

Due to the uncertainties involved in any accelerated vibration test approach, it would be judicious to avoid excessive accelerations. A 3 db increase, rather than 6 db, would introduce much less uncertainty, but still provide a sufficient test acceleration to effectively shorten a 28-hour test.

For high vibration levels, exceeding 15 or 20 g rms, encapsulation of boards is desirable, but conventional encapsulents, such as the polyurethanes and epoxies, render the electronic package unrepairable. The Sandia Corporation has extended vibration life by filling the entire cavity of an electronic package with loose phenolic microballoons, reducing their PC board amplification from 28 to 6. For manned missions, the use of microballoons would create crew safety and contamination concerns. Further evaluation and development testing is recommended to identify and select other easily removable encapsulants which could be used in off-the-shelf hardware to allow the utilization of such hardware in future programs involving reusable vehicles and long vibration exposures.

F. TOLERANCE FUNNELING GUIDELINES

To reduce the incidence of extremely costly failures at the launch complex, and at all other high levels of assembly, it is essential that the functional test requirements for a given hardware item be most stringent during the earliest stages of fabrication, and progressively less stringent as the hardware is moved through successive testing to the final countdown. This philosophy, referred to as Tolerance Funneling, or Triangular Tolerances, insures that marginal hardware is detected early in the life cycle where corrective action is least costly and most readily applied. It is extremely costly and bad practice to employ the same functional requirements throughout the life cycle, since small shifts or drift in either the hardware or in the test instruments will cause equipment to be rejected late in the life cycle. Where the philosphy of tolerance funneling is recognized and accepted, the problem that then exists is that each different designer has his own approach to establishing the tolerance funnel.

Chapter VII of Volume IV presents tolerance funneling approach that can produce a more consistent and uniform approach within a given program.